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PROVISIONAL APPLICATION FOR PATENT COVER SHEET

This is a request for filing a PROVISIONAL APPLICATION FOR PATENT under 37 CFR 1.53(c).

INVENTOR(S)

Given Name (first and middle [if any])	Family Name or Surname	Residence (City and either State or Foreign Country)
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Additional inventors are being named on the ___ separately numbered sheets attached hereto

TITLE OF THE INVENTION (500 characters max)

FLUIDIC ADAPTIVE LENS

Direct all correspondence to: **CORRESPONDENCE ADDRESS**

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☐ Firm or Individual Name					
Address					
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ENCLOSED APPLICATION PARTS *(check all that apply)*

☑ Specification *Number of Pages* 39
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METHOD OF PAYMENT OF FILING FEES FOR THIS PROVISIONAL APPLICATION FOR PATENT

☑ Applicant claims small entity status. See 37 CFR 1.27.
☐ A check or money order is enclosed to cover the filing fees
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The invention was made by an agency of the United States Government or under a contract with an agency of the United States Government.

☐ No.
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Respectfully submitted,

SIGNATURE [signature]

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U.S. PROVISIONAL PATENT APPLICATION

FOR

FLUIDIC ADAPTIVE LENS

by

Yu-Hwa Lo and De-Ying Zhang

FLUIDIC ADAPTIVE LENS

CROSS-REFERENCE TO RELATED APPLICATIONS

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STATEMENT REGARDING FEDERALLY SPONSORED RESEARCH OR DEVELOPMENT

[0001] This invention was made with United States Government support awarded by the following agencies: Defense Advanced Research Projects Agency (DARPA) Grant No. F49620-02-1-0426; and Air Force Office of Scientific Research (AFOSR) Grant No. F49620-02-1-0426. The United States Government has certain rights in this invention.

FIELD OF THE INVENTION

[0002] The present invention relates to optical lenses and more particularly relates to vision correction lenses and zoom lenses such as are employed in various optical systems.

BACKGROUND OF THE INVENTION

[0003] Optical lenses are employed in a variety of devices for many purposes such as modifying focus and magnification. Many conventional devices that employ optical lenses use lenses that are made from solid materials, such that the optical properties of the lenses (e.g., their focal distances) remain constant or nearly constant over time. For example, eyeglasses used for vision correction typically are made of solid materials such as glass and plastic. Similarly, cameras and other optical systems such as microscopes, video monitors, video recorders, copy machines, scanners, etc. commonly employ solid lenses.

[0004] Although lenses made from solid materials generally maintain their optical properties over time, the use of such lenses also has numerous disadvantages. With respect to vision correction lenses, for example, the power of vision correction is fixed at the time of fabrication of the lenses. As a consequence, today's eyeglasses

lenses cannot be mass produced at low cost because they have to be specially fabricated for each and every patient. Since each patient has his/her unique power requirement for eye correction, one has to see an ophthalmologist or optometrist to measure his/her eye correction power first before having the vision correction lenses fabricated. In addition, machining glass or plastic material to the precise shape of a lens according to a prescription is, by itself, a relatively high-cost and low throughput process. Often, it takes several days or even weeks for patients to receive a new pair of eyeglasses. In comparison with certain off-the-shelf vision products such as sunglasses, vision-correcting eyeglasses designed and fabricated using current technology are particularly expensive and complicated to manufacture.

[0005] Further, vision correction lenses used in today's eyeglasses do not have the flexibility to handle various situations with which wearers are often confronted. For example, the optimal eye correction for a given individual frequently varies depending upon a variety of factors, such as the person's age, the person's lifestyle, and various practical circumstances. Consequently, an adult typically needs to replace his or her eye correction lenses every few years. For juveniles or adolescents, updating of vision correction eyeglasses often is required more frequently than for adults.

[0006] For certain persons, particularly persons in their 50s and over, the vision correction that is needed for viewing near objects can be very different from the vision correction that is needed for viewing distant objects. To provide different levels of vision correction via a single pair of eyeglasses, many of today's eyeglasses employ bifocal lenses (or even tri-focal or otherwise multi-focal lenses), in which different sections of a given lens provide different optical properties. Yet such bifocal lenses offer at best an inconvenient solution to the problem of how to provide varying levels of vision correction on a single pair of eyeglasses. Traditionally, bifocal lenses employ lenses that are formed from pairs of lens portions that are positioned or fused adjacent to one another along a midline of the lens. Because the midline between the lens portions is a perceptible boundary between the lens portions, such lenses are often cosmetically undesirable.

[0007] Although newer bifocal lenses are available that are not as cosmetically undesirable, insofar as the lenses are graded such that there is only a gradual change of correction power from region to region on the lens and such that a clear boundary separating different regions of the lens does not exist, such newer bifocal lenses nevertheless share other problems with traditional bifocal lenses. In particular, because different portions of the lenses have different vision correction characteristics, the wearer's field-of-view via the lenses at any given time or circumstance is still compromised insofar as only certain portions of the lenses provide the appropriate optical characteristics for the wearer at that time/circumstance.

[0008] Additionally, while many persons do not require bifocal lenses, these persons can nevertheless prefer that their eyeglasses provide different amounts of vision correction in different situations. For example, the preferred amount of vision correction for a person when driving a car or watching a movie can differ from the preferred amount of vision correction for that person when reading a book or working in front of a computer screen.

[0009] For at least these reasons, therefore, it is apparent that the use of solid lenses with fixed optical properties in eyeglasses is disadvantageous in a variety of respects. Yet the disadvantages associated with using solid lenses with fixed optical properties are not limited to the disadvantages associated with using such lenses in eyeglasses/eyewear. Indeed, similar disadvantages occur in a variety of devices that employ lenses, such as cameras, microscopes, video monitors, video recorders, copy machines, scanners, etc.

[0010] Further, the use of solid lenses with fixed optical properties entails additional disadvantages in systems that employ combinations of lenses that interact with one another to provide overall optical properties. Such systems include, for example, zoom lens systems in which two or more optical lenses of fixed optical properties are moved relative to one another to change optical properties of the overall combination of lenses forming the zoom lens. Because the optical properties of the lenses used in such systems are fixed, the overall optical properties of the combinations of lenses depend upon other factors, particularly the relative

positioning of the lenses. Consequently, to provide the desirable features and capabilities associated with systems such as zoom lens systems, complicated and expensive mechanical and/or other components and techniques must be employed to achieve the desired effects.

[0011] In particular with respect to zoom lens systems, conventional systems with zooming capability are typically more expensive and often more bulky/heavy than systems without such capability. The most important figure of merit for zoom lenses is the zoom ratio. The higher the zoom ratio is, the more costly the system becomes. A typical camera has an optical zoom ratio of about 3, and some high-end imaging systems have a zoom ratio of greater than 10. Currently, all optical zoom lenses achieve zoom-in and zoom-out functions via change of the distance between lenses. This involves high precision mechanical motions of the lenses over a typical range of several centimeters. To provide highly-precise, reliable relative movement of the lenses typically requires a mechanical system that is complicated, slow, bulky and expensive.

[0012] The requirement for changing lens distance for zooming has become a roadblock for incorporating zooming features into many new and emerging applications. Many modern "electronic gadgets" including cell phones, personal digital assistants (PDAs), and notebook computers are equipped with CCD or CMOS cameras. Implementation of cameras into such gadgets has evolved from being a novelty to being a standard feature, and many such gadgets now support imaging functions involving not just imaging but also recording, videophone capabilities, and video conferencing. Yet conventional zoom lenses are difficult to incorporate into the these small electronic and optical devices.

[0013] Therefore, it would be advantageous if one or more new types of lenses and/or lens systems could be developed that alleviated the disadvantages associated with using solid lenses having fixed optical properties as discussed above. In particular, it would be advantageous if a new type of lens or lens system could be developed for implementation in eyeglasses that made it possible to easily and inexpensively adjust optical characteristics of the eyeglasses without entirely replacing the lenses. It would further be advantageous if the optical characteristics

of the lenses could be flexibly varied over a wide spectrum, rather than simply to a limited number of discrete levels. It additionally would be advantageous if the optical properties of the entire lenses could be varied in unison such that changes in the optical properties of the lenses would apply to an entire range of vision of a wearer of eyeglasses employing the lenses, rather than merely a portion of that range of vision.

[0014] It further would be advantageous if the new type of lens or lens system could also be implemented in other systems that employ lenses such as cameras, microscopes, video monitors, video recorders, copy machines, scanners, etc. It additionally would be advantageous if the new type of lens or lens system could be implemented in zoom lens systems in a manner that reduced the need for complicated mechanical systems for controlling relative positioning of lens within the zoom lens system. It also would be advantageous if a zoom lens system employing the new type of lens or lens system could be compactly implemented on one or more physically small "electronic gadgets" such as cell phones, personal digital assistants (PDAs), or notebook computers.

BRIEF SUMMARY OF THE INVENTION

[0015] The present inventors have recognized that many of the above-mentioned disadvantages associated with conventional eyeglasses and optical systems, including systems employing multiple lenses such as zoom lens systems, can be alleviated or eliminated if the eyeglasses or optical systems employ lenses that are variable or adaptive in terms of their optical properties. The present inventors further have discovered that lenses having adaptive optical properties can be formed, without the use of complicated mechanical or moving parts, through the use of one or more optically conductive flexible diaphragms/membranes that respectively separate pairs of media having different refractive indices, where variable fluidic pressures applied to the flexible diaphragms/membranes so as to alter the relative positioning of the media about those diaphragms/membranes.

[0016] In particular, the present invention relates to a lens including a first partition that is flexible and optically transparent, and a second partition that is coupled to the

first partition, where at least a portion of the second partition is optically transparent, and where a first cavity is formed in between the first partition and the second partition. The lens further includes a first fluidic medium positioned within the cavity, the fluidic medium also being optically transparent, and a first device capable of controlling a parameter of the fluidic medium. When the parameter of the fluidic medium changes, the first partition flexes and an optical property of the lens is varied.

[0017] Additionally, the present invention relates to a multi-lens apparatus that includes a first fluidic adaptive lens, a second fluidic adaptive lens, and an intermediate structure coupling the first and second fluidic adaptive lenses, where the intermediate structure is at least partly optically transparent.

[0018] Further, the present invention relates to a method of fabricating a fluidic adaptive lens device. The method includes providing a structure having an open-ended cavity formed therewithin, and affixing a flexible membrane to the structure in a manner sealing the cavity except insofar as at least one channel within at least one of the structure and the membrane allows for communication of a fluid with respect to the cavity. The cavity is capable of being filled with the fluid so that the structure, flexible membrane and fluid interact to form a first lens device.

BRIEF DESCRIPTION OF THE DRAWINGS

[0019] Figs. 1 and 2 show, in simplified schematic form, cross-sectional views of a convex fluidic adaptive lens and a concave fluidic adaptive lens, respectively;

[0020] Figs. 3(a) and 3(b) show, in more detail, cross-sectional views of exemplary convex and concave fluidic adaptive lenses of Figs. 1 and 2, respectively, along with related support structures;

[0021] Figs. 4 and 5 show two cross-sectional views of other exemplary embodiments of fluidic adaptive lenses that maintain a constant outer shape;

[0022] Fig. 6 shows in schematic form a zoom lens system employing at least one fluidic adaptive lens;

[0023] Fig. 7 shows a cross-sectional view of an exemplary fluidic adaptive lens capable of being used to achieve a wide focal-distance tuning range;

[0024] Fig. 8 is a graph showing how a focal length of the fluidic adaptive lens of Fig. 7 varies with fluidic pressure in one embodiment;

[0025] Fig. 9(a)-(d) show in schematic form steps of an exemplary process for constructing a zoom lens system utilizing fluidic adaptive zoom lenses;

[0026] Fig. 10, 11(a) and 11(b) show three cross-sectional views of exemplary embodiments of fluidic adaptive lenses that are capable of being employed in the zoom lens system of Fig. 6;

[0027] Fig. 12(a)-(b), 13(a)-(c) and 14(a)-(d) show cross-sectional views of exemplary embodiments of zoom lens systems employing various combinations of the lenses shown in Figs. 10, 11(a) and 11(b); and

[0028] Fig 15 is a graph showing the variation of magnification provided by an exemplary zoom lens system, in accordance with one of the embodiments of Figs. 12-14, as a function of front lens power.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENT

[0029] The present invention relates to the use of one or more fluidic adaptive lenses in a variety of environments such as in eyeglasses and zoom lens systems. Figs. 1-5 generally relate to the design of fluidic adaptive lenses that can be implemented in eyeglasses for the purpose of providing dynamically-adjustable vision correction power. Figs. 6-15 generally relate to the design of fluid adaptive lenses and combinations of such lenses that can be implemented in zoom lens systems in cameras and the like to provide variable zooming capability without the need for complicated mechanical devices for physically moving multiple lenses toward or away from one another.

[0030] Although Figs. 1-15 relate to the design and implementation of fluidic adaptive lenses for use in eyeglasses and zoom lens systems, the present invention is also intended to encompass the use of these or similar fluidic adaptive lenses in a variety of other applications and circumstances including, for example, a wide variety of other electronic and other devices such as microscopes, video monitors, video recorders, copy machines, scanners, cell phones, personal digital assistants (PDAs), notebook computers, and magnifying glasses.

[0031] Referring to Figs. 1 and 2, exemplary fluidic adaptive lenses capable of being implemented in eyeglasses are shown in schematic form. Fig. 1 shows the general situation of a first fluidic lens 1 that can be used to correct hyperopia (farsightedness). As shown, the fluidic lens 1 is a convex adaptive vision correction lens that contains a first medium 20 that is a higher index fluid, a second medium 10 that is a lower index fluid, and a flexible membrane (or diaphragm) 30 that separates the two media. The flexible membrane 30 bends towards the lower index side when the pressure of the higher index fluid is greater than that of the lower index fluid. In contrast to Fig. 1, Fig. 2 shows the general situation of a second fluidic lens 2 that can be used to correct myopia (nearsightedness). As shown, the fluidic lens 2 is a concave adaptive vision correction lens that contains a first medium 20 that is a higher index fluid, a second medium 12 that is a lower index fluid, and a flexible membrane (or diaphragm) 32 that separates the two media. The membrane 32 bends towards the higher index side when the pressure of the lower index fluid is greater than that of the higher index fluid.

[0032] The respective flexible membranes 30,32 are deformed by the pressure differences between the respective pairs of media 10,20 and 12,22. For example, if the pressure on the higher index medium side is greater than that of the lower index medium side, the membrane will bend towards the low index medium, as shown in Fig. 1, to form an effective convex lens capable of correcting the hyperopia (farsightedness) problem. On the other hand, if a higher fluidic pressure exists on the low-index medium side, the membrane will bend towards the high-index medium to form an effective concave lens capable of correcting the myopia (nearsightedness) problem (see Fig. 2).

[0033] Turning to Figs. 3(a) and 3(b), exemplary fluidic lenses 36,46 are shown in cross-section. The lenses 36,46 shown in greater detail exemplary structures that can be employed as the lenses 1,2 shown schematically in Figs. 1 and 2, respectively. That is, Figs. 3 (a) and (b) respectively show convex and concave lenses 36 and 46, respectively. Further as shown, each of the lenses 36 and 46 respectively includes a segment of transparent rigid material 31 and 41, respectively; a first fluidic medium 32 and 42, respectively, a second fluidic medium 33 and 43,

respectively, and a flexible membrane (or diaphragm) 34 and 44, respectively. In the present embodiment, the second fluidic media 33,43 are shown as air outside of the lenses 36,46, although those fluidic media could be other fluids (gaseous or liquid) as well.

[0034] Additionally, each of the lenses 36,46 includes respective walls 37,47 that support the respective membranes 34,44 with respect to the respective transparent rigid materials 31,41. The walls 37,47 along with the membranes 34,44 and transparent rigid materials 31,41 define respective internal cavities 38,48 within which are the first fluidic media 32,42. The walls 37,47 also define respective channels 39,49 by which the first fluidic media 32,42 can enter and exit the cavities 38,48. Arrows 35,45 respectively represent the directions of the flow (and/or pressure) of the media 32,42 with respect to the cavities 38,48 that are appropriate for causing the respective lenses 36,46 to become convex and concave, respectively. As shown, the first fluidic medium 32 tends to flow into the cavity 38 causing the membrane 34 to expand outward while the first fluidic medium 42 tends to flow out of the cavity 45 tending to cause the membrane 44 to contract inward.

[0035] By controlling the amounts of the first fluidic media 32,42 that flow in and out of the cavities 38,48 (which can depend upon the pressure of those media), the optical properties of the lenses 36,46 can be varied. In particular, because in the present embodiment the second fluidic media 33,43 are the air of the atmosphere, by applying a positive pressure to the first fluidic medium 32 (e.g., a pressure greater than the atmospheric pressure), the membrane 34 tends to expand outward as shown in Fig. 3(a), and by applying a negative pressure to the first fluidic medium 42 (e.g., a pressure less than the atmospheric pressure), the membrane 44 tends to contract inward as shown in Fig. 3(b).

[0036] Although the lenses 36,46 shown in Figs. 3(a)-(b) are capable of operating as lenses (e.g., capable of causing light to be focused or to be dispersed), the structures of these lenses are not preferred. Because the membranes 34,43 in the present embodiment are exposed to the outside atmosphere and outside environment, atmospheric pressure changes, temperature changes and/or external impacts all can damage or change the optical properties of the lenses 36,46, such that the lenses can

suffer from reliability, stability (including drift of the lenses' optical properties), and performance issues. Particularly in the mode of the concave lens 46 of Fig. 3(b), the fluidic chamber has to maintain a negative pressure relative to the atmosphere, which requires an air-tight design that is much harder to achieve and keep stable than a leak-tight design for positive fluid pressure. While suitable for some applications, the lenses 36,46 are not preferred for use in eyeglasses.

[0037] Two improved designs for fluidic adaptive lenses that are capable of being employed as the lenses 1 and 2 of Figs. 1 and 2, and that are more robust and stable in operation than the lenses 36,46 of Figs. 3(a)-(b), are shown in Figs. 4 and 5 as lenses 50 and 60, respectively. To minimize the influence of the environment such as atmospheric pressure, the lenses 50,60 employ rigid materials to form all (or nearly all) of the outer surfaces of the lenses. As shown, the lens 50 of Fig. 4 in particular includes two fluid chambers, while the lens 60 of Fig. 5 includes three fluidic chambers.

[0038] Referring to Fig. 4, the lens 50 includes the following components: transparent, rigid outer surfaces 51 (on both sides of the lens) that are capable of keeping the outer shape of the lens unchanged like conventional solid lenses; a flexible membrane (or diaphragm) 54 positioned in between the rigid outer surfaces 51; walls 57 that support the membrane 54 in relation to the surfaces 51; a lower index fluidic medium 52 contained within a first cavity 58 defined by the membrane 54, the walls 57 and one of the rigid outer surfaces 51; a higher index fluidic medium 53 contained within a second cavity 59 defined by the membrane 54, the walls 57 and the other of the rigid outer surfaces 51; and first and second channels 55 and 56 that extend through the walls 57 and respectively connect the first and second cavities 58 and 59 with fluid reservoirs (not shown). In alternate embodiments, the channels 55,56 can extend through the surfaces 51 rather than through the walls 57.

[0039] The lens 50 can be employed either as the convex lens 1 of Fig. 1 or the concave lens 2 of Fig. 2 depending upon the pressures of the first and second media 52,53. When the pressure of medium 52 is greater than that of medium 53, the membrane 54 bends towards the cavity 59 and the device behaves as a concave lens

for myopia. When the pressure difference between the two chambers is reversed, the lens behaves as a convex lens for hyperopia. The pressures of each fluidic chamber can be controlled by one or more mechanical or electromechanical actuator(s), and the curvature of the membrane is determined by the pressure difference between the two chambers.

[0040] Regardless of the particular magnitude/sign of the pressure difference between the first and second media 52,53, and regardless of the atmospheric pressure, the outer shape of the lens does not change since it is defined by the rigid surfaces. Thus, in contrast to the lens designs of Figs. 3(a)-(b), the lens 50 of Fig. 4 does not require maintaining a negative pressure to achieve the concave structure, so the structure does not need to be made air-tight. Because the viscosity of air and liquid differs by many orders of magnitude, it is far easier to achieve a leak-tight structure than an air-tight structure. Finally, since it is the fluidic pressure difference that determines the curvature of the membrane, the lens property is independent of the atmospheric pressure that is equally applied to both fluidic media. On the other hand, temperature changes will cause a very minor index change of the media through the thermo-optic effect, producing unnoticeable effect for eyeglasses.

[0041] As for the lens 60 shown in Fig. 5, this lens employs transparent rigid outer surfaces 61, two flexible membranes 62 positioned in between the outer surfaces 61, walls 68 supporting the membranes 62 in relation to the outer surfaces 61, a low index fluid 63 within two outer cavities 69 defined by the walls 68, the membranes 62 and the outer surfaces 61, and a high index fluid 64 within an inner cavity 70 defined by the walls 68 and the two membranes 62. Three fluidic channels 65, 66 and 67 respectively connect the respective cavities 69 and 70 to fluid reservoirs (not shown), which can be two (e.g., one for the high index fluid and one for the low index fluid) or three (e.g., one corresponding to each of the cavities) in number. When the pressure of the high index fluid 64 is greater than the pressure of the low index fluid 63, the lens behaves as a convex lens for hyperopia. When the pressure difference is reversed, the lens behaves as a concave lens for myopia.

[0042] Because the lens 60 has rigid outer surfaces 61 just like the lens 50, the lens 60 has the same advantages as the lens 50 in terms of stability, reliability and

performance. In alternate embodiments, the high index fluid can be in the outer cavities 69 and the low index fluid can be in the inner cavity 70, or each of the cavities can contain fluid having the same index or having an index different than each of the other cavities.

[0043] Use of fluidic adaptive lenses such as those discussed with reference to Figs. 1-5 (and particularly those of Figs. 4 and 5) in eyeglasses provides numerous benefits. The lenses can be mass-produced as identical units and let the eyeglasses wearers to set the extent of sight correction they need. Therefore the design offers a fundamentally low cost solution from the production point of view. Also, the power of the adaptive corrective lenses can be dynamically adjusted by wearers themselves. This could significantly cut down the need and time to visit optometrists to obtain prescriptions for eyeglasses. Additionally, one can continuously adjust the power of correction over a very wide range for the optimal vision correction, as opposed to finding the nearest fit based on the set of lenses available for optometrists.

[0044] Further, there is no need to buy new eyeglasses when the required vision correction changes. Since people's vision changes gradually, patients wearing tunable eyeglasses will not suffer from the compromised vision before the eyeglasses replacement. Also, the tunable fluidic lenses can even become better substitutes for the solid-state lens set to helping optometrists produce a more accurate prescription for their customers. Additionally, the lenses can eliminate any undesirable cosmetic effect for those who need bifocal lenses. Instead of utilizing bifocals (or other similar multi-focal lenses), a person can simply wear a pair of eyeglasses capable of being modified in its optical properties as necessary for user's circumstance.

[0045] In one embodiment, fluidic adaptive lenses such as that shown in Fig. 4 can be manufactured in the following manner. In a first step, two cavities are formed using plastic polymer material such as polydimethylsiloxane (PDMS) or polyester. The typical dimension of the cavities is a few centimeters in diameter and millimeters in height. The cavities can be understood to include both the rigid outer surfaces 51 and the walls 57 shown in Fig. 4. In a second step, a thin plastic

polymer membrane is formed. The membrane thickness is in the order of 100 μm and the material is flexible. The membrane will be used as a flexible diaphragm separating the chambers filled with media of different indices of refraction. Then, in a third step, the plastic polymer membrane formed in step 2 is bonded to one of the cavities formed in step 1 to form a closed chamber. Then the other side of the membrane is bonded to the second cavity. The result is the formation of a lens having two cavities separated by the membrane.

[0046] Then, in a fourth step 4, channels are formed on the sides of both of the cavities for the inlet and outlet of the fluid media. In a fifth step, the channels arc connected to fluid reservoirs. Further, in a sixth step, actuators are incorporated to allow for the control of the fluid media into and out of the cavities (e.g., by controlling the pressures of the fluid media). Exemplary actuators can include, for example, small frame-mounted pumps, piezoelectric actuators, micro-electro-mechanic-system (MEMS) actuators, or teflon-coated set screws to control and the pressure of each fluid chamber. Finally, in a seventh step, fluidic media of different refractive indices are introduced into the respective cavities from the reservoirs. Any of a variety of fluidic media can be employed. For example, one of the media can be water having an index of 1.3 and the other medium may be oil having a refractive index of about 1.6. This completes the fabrication of vision correction tunable lens. The lens can then be mounted to the frame of the eyeglasses.

[0047] To estimate the adjustment power of the adaptive vision correction lenses, one can assume that the diameter of the adaptive corrective lenses is 20 millimeters. Compared to the diameter change of human pupil from about 2 millimeters in sunlight to 8 millimeters in the dark, this lens diameter is large enough for eyeglasses. In order to estimate the power adjustment range of the adaptive correction lens, one can further assume that the low index medium is air with a refractive index of 1 and the high index medium is water with a refractive index of 1.333. Using a ray-tracing simulation program or the thin lens approximation for an analytic solution, we have found that the maximum positive power and negative power of the above adaptive corrective lens is 12.8 D (diopters) and –12.8 D (diopters), respectively. Hence the total adjustment range for the adaptive corrective

lens is from –12.8 D (diopters) to 12.8 D (diopters), corresponding to an uncorrected visual acuity of 0.017minute^{-1} for hyperopia (farsightedness) and 0.022 minute^{-1} for myopia (nearsightedness).

[0048] Further, if silicone oil is utilized as the high index medium (refractive index is about 1.5) and water as the low index medium, then the total adjustment range for such adaptive lenses becomes from 6.4 D (diopters) to –6.4 D (diopters), corresponding to an uncorrected visual acuity of 0.036minute^{-1} for hyperopia and 0.042minute^{-1} for myopia. If silicone oil is used as the high index medium (refractive index is about 1.5) and air is used as the low index medium, then the total adjustment range for such adaptive lenses becomes from 19.2 D (diopters) to –19.2 D (diopters), corresponding to an uncorrected visual acuity of 0.010minute^{-1} for hyperopia and 0.016minute^{-1} for myopia. It will be known to those of ordinary skill in the art that a wide variety of fluids of different indices can be employed to make the lenses and allow the lenses to take on a variety of optical properties, which can be easily analyzed based on the principle of geometric optics. Likewise, the particular materials used to form the rigid outer surfaces, walls and flexible membranes can include any of a variety of plastic, acrylic and other materials, and can vary from embodiment to embodiment.

[0049] In accordance with certain embodiments of the present invention, two or more fludic adaptive lenses can also be employed in devices that require multiple lenses. In Figs. 6-15, various implementations of pairs of fluidic adaptive lenses to form zoom lens systems (and, in particular, zoom lens systems that can be implemented in compact electronic or other devices) are shown. However, the present invention is also intended to encompass other embodiments of multi-lens systems employing more than two lenses, lens systems in which one or more of the lenses are fluid adaptive lenses and other(s) of the lenses are conventional, solid (or other types of) lenses, and lens systems that operate to perform other functions such as the zooming functions that are performed by zoom lens systems.

[0050] Referring specifically to Fig. 6, a two-lens optical zoom system 71 includes a front lens 72 (near an object) and a back lens 74 (near an image of the object) that are separated by a distance d that is constant, where in between the lens is typically

an optical medium 76. Depending upon the embodiment, the medium 76 between the two lenses 72,74 can be any of a variety of optically conductive materials including, for example, air, glass, polymer, or anything transparent at the wavelengths of interest. For simplicity without losing the generality, it can be assumed that both of the lenses 72,74 are thin so that thin lens approximations can be applied throughout the analysis. Each of the lenses 72,74 has a respective imaging distance l_1 and l_2, respectively, and the latter of which is fixed. Zooming is achieved by varying the respective focal distances f1 and f2 of the respective lenses 72,74 (these and other notations/variables used to describe characteristics of the two-lens optical zoom system 71 are shown in Fig. 6).

[0051] Following the conventions of lens analysis, the variable Φ of a lens is defined as the power of the lens or lens system, which is also equal to the inverse (reciprocal) of the focal distance f of the lens. While each of the lenses 72,74 has its own values for Φ (e.g., Φ_1 and Φ_2, respectively), of particular interest for the two-lens optical zoom lens 71 is an overall power of the system Φ_τ. This quantity Φ_τ can be determined as a function of the power of each of the lenses 72,74 and other parameters as follows:

$$\Phi_2 = \frac{1}{l_2} + \frac{1 + \Phi_1 \times l_1}{\Phi_1 \times l_1 \times d + d - l_1}. \qquad (1)$$

$$\Phi_\tau = -\frac{d}{l_2} \times \frac{\left(\Phi_1 + \dfrac{d - 2l_1}{2d \times l_1}\right)^2 - \dfrac{d^2 + 4l_1 \times l_2}{4d^2 \times l_1^2}}{\Phi_1 + \dfrac{d - l_1}{d \times l_1}} \qquad (2)$$

[0052] Equation 1 shows that for given object and image distances (l_1, l_2) and lens spacing d, the focal distance Φ_2 (or power) of the second lens is uniquely determined by the focal distance of the first lens Φ_1. Further, Equations (1) and (2) together show that, for a given object conjugate, the overall power of this two-lens system (Φ_τ) can be adjusted by varying f_1 and f_2 (or Φ_1 and Φ_2), the focal distances of both lenses. In comparison, conventional designs using lenses with fixed focal distances (e.g., solid lenses) have to rely on varying the lens spacing d and the image distance

l_2 to adjust the power of the system. Zoom ratio (ZR), a parameter of merit for zoom lens systems, is defined as the ratio of the maximal achievable power and the minimal achievable power (e.g., ZR = Φ_{max} / Φ_{min}). From Equations (1) and (2), it is evident that, to achieve a high zoom ratio for given object and image distances, one should vary the focal distances as much as possible. These concepts and conclusions also hold for zoom lens systems having more than two lenses.

[0053] Although, in principle, the concept of zooming via varying the focal distances could be applied using any type of adaptive lens, no tunable lenses reported to date have had a wide enough tuning range to be practical. For example, the shortest focal length ever demonstrated in liquid crystal adaptive lenses is about 200 mm for a lens aperture of around 5mm, which is insufficient to allow appreciable zooming effect. Both theoretical analysis and ray tracing simulation indicate that highly effective zoom lenses can be achieved only if the focal distance of the lenses can be tuned continuously from a distance much greater than the lens aperture to comparable to or shorter than the aperture. In other words, for a 5mm lens aperture, one would need to acquire a range of focal length from several centimeters to 5 mm or less, a value 40 times less than the shortest focal length demonstrated in state-of-the-art liquid crystal lenses.

[0054] Further, while an even higher zoom ratio can be obtained if not only the focal distance of the lens but also the "type" of the lens can be adapted or converted between being a positive lens (having a positive focal distance such as a convex lens) and a negative lens (having a negative focal distance such as a concave lens) and vice versa. Liquid crystal lenses are (at least at the present time) incapable of being changed in their type.

[0055] In accordance with the present invention, the two-lens optical zooming system 1 (or similar systems) when equipped with fluid adaptive lenses can achieve sufficiently high zoom ratio without varying the distance separating the lenses 72,74 within the system. By using fluid adaptive lenses, not only can the focal distances of the lenses 72,74 be widely varied or tuned, but also the lenses can be changed or converted in their type. Figs. 7-15 show various structures that can be used for the lenses 72,74 and lens system 71 as well as a fabrication technique for such lenses.

However, the present invention is also intended to encompass other structures and fabrication techniques for creating zoom lens systems by way of fluidic adaptive lenses that will be evident to those of ordinary skill in the art.

[0056] The component structures of a fluidic adaptive lens 75 that can be used as each of the lenses 72,74 is shown in Fig. 7. As shown, the lens 75 includes a deformable/flexible membrane (or diaphragm) 81 that is coupled the rim of a cup-shaped structure 85 having a fluid-containing lens cavity 82 that includes a fluidic medium 83. One or more channels 84 through the cup shaped structure 85 allow for the fluidic medium 83 to enter/exit the cavity 82 from/to a fluid reservoir (not shown). When the fluidic pressure inside the cavity 82 changes, the curvature of the membrane 81, and therefore the lens shape, changes as well, producing different focal distances. Using an elastic silicone-based material (e.g. PDMS) of low Young's modulus (e.g. 1 M Pascals) as the membrane 81, a large lens shape change can be achieved (e.g., from a concave or flat surface to a convex surface) as the pressure inside the lens chamber varies (e.g., from a negative to a positive value relative to the pressure outside the chamber). To achieve an even broader tuning range of focal distance, one can use high index fluid as the lens medium.

[0057] Fig. 8 shows the dependence of the focal distance f of the lens 75 on the fluidic pressure with different lens media, namely, DI water (n=1.33) and sodium chromate (n = 1.50), assuming a 20 mm lens aperture. As shown, not only can the focal distance of the lens 75 be varied by modifying the fluidic pressure, but also the type of lens (e.g., negative or positive) as indicated by negative of positive focal distance values can be changed by modifying the fluidic pressure. This is the first time that a minimal focal distance (20 mm for H_2O and 14 mm for sodium chromate in positive lens and –17 mm for H_2O and -6 mm for sodium chromate in negative lens) shorter than the lens aperture is demonstrated. As the previous analysis indicates, a single adaptive lens having both a wide focal distance tuning range and lens type convertibility as discussed above makes it possible to achieve a high performance zoom lens system without the need for varying the distance between the lenses.

[0058] The flexibility in the choice of the materials from which the lens system 71 can be built, and particularly the flexibility in the choice of materials that can be used to form the medium 76, offers many possibilities for forming "integrated zoom lenses" and for wafer scale production of zoom lenses and zoom lens arrays. Figs. 9(a)-(d) show schematically how an exemplary two-lens structure 90 capable of being employed within the two-lens optical zoom system 71 could be fabricated at low cost in an exemplary wafer-scaled batch process. As shown in Fig. 9(a), a transparent substrate (e.g. a glass substrate or polymer substrate) 91 of proper thickness is chosen and two wafers 92 patterned with respective cavities 96 are fabricated first. The patterns defining the cavities 96 can be formed using a soft lithography or molding process. Then, as shown in Fig. 9(b), the two wafers 92 are bonded to opposing sides of the substrate 91 in a manner such that the cavities 96 are open outward away from the substrate.

[0059] Further, as shown in Fig. 9(c), two handle wafers 94 each with a respective membranes 93 deposited along a side thereof are provided. The handle wafers 94 provide mechanical support for bonding the membranes 93 onto rims 95 of the wafers 92. Finally, as shown in Fig. 9(d), the handle wafers 94 are removed from the membranes 93, leaving the completed two-lens structure 90, which includes a first fluidic adaptive lens body 97 capable of facing an object and a second fluidic adaptive lens body 98 capable of facing an imaging plane. Where multiple such two-lens structures 90 are created simultaneously on a single wafer (e.g., a single wafer comprising several of the substrates 91) by way of a batch process, such two-lens structures can be separated from one another by dicing the wafer into individual two-lens structures. Once an individual two-lens structure 90 is obtained, it can be employed in the two-lens optical zoom system 71 by connecting the two-lens structure 90 to a fluidic system (e.g., to fluidic reservoirs, not shown), and filling the cavities 96 with the lens media of choice. Although channels allowing for fluidic media inflow/outflow with respect to the cavities 96 are not shown in Figs. 9(a)-(d), it is to be understood that such channels are provided (e.g., as indentations in the rims 95 of the wafers 92).

[0060] Of significance during the process shown in Figs. 9(a)-(d) is that there be good alignment between the cavities 96 used to form the first and second fluidic adaptive lens bodies 97,98. Because all the materials are transparent and the patterns are formed on large sized wafers, one can use either a contact aligner or the standard fixture of bonding machines (e.g. bonding machines produced by Karl Suss) to routinely achieve an alignment accuracy of a few micrometers. Assuming proper alignment of the cavities 96, the lens membrane 93, deposited on the silicon handle wafers 94, can be bonded to the lens chambers with less alignment concern. The process discussed here allows fabrication of zoom lenses of nearly any size (from < 0.1 mm to centimeters) for various applications.

[0061] By way of this process shown in Figs. 9(a)-(d), two-lens optical zoom systems can be achieved on a high volume, low cost manufacturing basis. However, the present invention is also intended to encompass a variety of other structures and fabrication processes that employ the same or similar principles and the same or similar lens fabrication processes as shown with respect to Figs. 9(a)-9(d). Through the manufacture of such various structures by way of such various techniques, a variety of different fluidic lens structures other than the structures 90 can be obtained in order to meet different application requirements. Figs. 10-15 in particular show additional exemplary lens system designs that can be attractive for implementation in devices where, to improve the robustness of the lens systems, it is desirable that the lens membranes not be directly exposed to the outside environment or, even further, desirable that all lens membranes be contained within the inside body of the zoom lens.

[0062] Fig. 10 and Fig. 11 show two additional fluidic adaptive lens structures 100, 110 and 120 that can be employed as either of the lenses 72,74 for constructing two-lens optical zoom systems with good mechanical robustness. Fig. 10 in particular shows the lens structure 100 to include two outer surfaces 101 formed from a rigid material, a flexible membrane 102 positioned in between the outer surfaces 101 and supported therebetween by way of rigid walls 103. The walls 103 include fluidic channels 104 by which first and second internal cavities 105, 106, respectively, formed between outer surfaces 101 and the membrane 102 can be coupled to

respective fluidic reservoirs (not shown). The fluidic reservoirs provide first and second fluidic media 107, 108, respectively to the respective cavities 105,106, where the first fluidic medium typically (though not necessarily) differs in refractive index from the second fluidic medium, for example, the first fluidic medium can have a lower refractive index than the second fluidic medium.

[0063] As for the lens structures 110 and 120 of Fig. 11 (shown in Fig. 11(a) and Fig. 11(b), respectively), each of these lens structures includes a pair of flexible membranes 111 positioned in between a pair of rigid outer surfaces 112 and supported therebetween by way of walls 113. In between the flexible membranes 111 is defined an inner cavity 114, while in between each of the membranes and one of the rigid outer surfaces 112 is defined a respective outer cavity 115. The walls 113 contain inner and outer channels 116,117 that respectively allow for fluidic media to enter/exit with respect to the inner cavity 114 and the outer cavities 115, respectively. Typically, though not necessarily, the outer cavities 115 receive the same fluidic medium while the inner cavity 114 receives a fluidic medium different than that provided to the outer cavities 115. In the lens structure 110 of Fig. 11(a) in particular, a first fluidic medium 118 of lower refractive index is provided to the outer cavities 115, while a second fluidic medium 119 of higher refractive index is provided to the inner cavity 114. In the lens structure 120 of Fig. 11(b), in contrast, the first fluidic medium 118 of lower refractive index is provided to the inner cavity 114 while the second fluidic medium 119 of higher refractive index is provided to the outer cavities 115.

[0064] The fluidic adaptive lens structures 100,110 and 120 each contain two (or more) media separated by one or more membranes deformable by the pressure difference between the medium containing cavities. For example, if the pressure in the higher refractive index medium cavity is greater than that in the lower refractive index medium cavity, the membrane will bend towards the low index side to form an effective convex lens. Conversely, if a higher fluidic pressure exists in the low refractive index medium cavity, the membrane will bend towards the high refractive index side to form an effective concave lens. Thus both the lens type (either negative or positive) as well as the focal length of the fluidic lenses can be

modified/tuned via dynamic control of the curvature of the membrane, which is determined by the fluidic pressure difference between the two cavities on opposite sides of the membrane (and, in the case of the lens structures 110 and 120, possibly determined the fluidic pressures in each of the three cavities).

[0065] Because the lens structures 100,110 and 120 of Figs. 10-11 have outer surfaces (101 and 112, respectively) that are rigid, the devices are more resilient to outside disturbances. Further, because the outer surfaces 101,112 are rigid, the external shapes of the lens structures do not change even though the magnitudes and sign of the pressure differences within the cavities 105,106,114 and 115 changes. Consequently, such lens structures 100,110 and 120 can be easily concatenated to form two-lens optical zoom systems as well as multiple-lens (greater than 2 lens) optical zoom systems to further increase the zoom ratio. The pressure of each fluidic chamber can be controlled by mechanical, piezo-electric, electromagnetic, or electromechanical actuators; and the curvature of the membrane is determined by the pressure difference between the two adjacent chambers and the mechanical property of the membrane. Although various liquids can be employed as the fluidic media 107,108,118,119, it should be understood from the discussion concerning Fig. 7 that air can also be used as the low index medium; in this special case, a single-cavity fluidic adaptive lens can be constructed by removing the cavities(s) for the low index medium.

[0066] Figs. 12-14 show exemplary two-lens optical zoom systems 122, 124, 126, 128, 130, 132, 134, 136 and 138 constructed with various pairs of the fluidic lens structures 100,110 and 120 discussed in Figs. 10-11, which are separated by an intermediate optical medium 140 that is positioned between the lens structures. The optical medium 140 can take on a variety of forms, including forms such as those discussed above with respect to the substrate 91 of Fig. 9, and the medium can offer structural support for holding the pairs of lens structures together as well as simply provide an optically conductive medium. The two-lens optical zoom systems combine the lens structures 100,110 and 120 as follows: With respect to the system 122 of Fig. 12(a), this system combines two of the lens structures 100 having the same orientation, such that the second fluidic medium 108 of one of the lens

structures 100 is positioned closer to the optically conductive medium 140 while the first fluidic medium 107 of the other of the lens structures is positioned closer to the optically conductive medium. As for the system 124 of Fig. 12(b), this system combines two of the lens structures 100 in an oppositely-oriented manner, such that the same fluidic medium (in this case, the first fluidic medium 107) of each of the lens structures is positioned closer to the optically conductive medium 140.

[0067] With respect to the systems 126, 128 and 130 of Figs. 13(a), 13(b) and 13(c), respectively, these systems respectively combine two of the lens structures 110 of Fig. 11(a), one of the lens structures 110 of Fig. 11(a) along with one of the lens structures 120 of Fig. 11(b), and two of the lens structures 120 of Fig. 11(b). With respect to the systems 132 and 134 of Figs. 14(a) and 14(b), respectively, these systems respectively combine the lens structure 100 of Fig. 10 with one of the lens structures 110 of Fig. 11(a), where Fig. 14(a) shows the lens structure 100 in one orientation and Fig. 14(b) shows the lens structure 100 in an orientation opposite to that of Fig. 14(a). As for the systems 136 and 138 of Figs. 14(c) and 14(d), respectively, these systems respectively combine the lens structure 100 of Fig. 10 with one of the lens structures 120 of Fig. 11(b), where Fig. 14(c) shows the lens structure 100 in one orientation and Fig. 14(d) shows the lens structure 100 in an orientation opposite to that of Fig. 14(c). Figs. 12-14 are only intended to show exemplary arrangements of the fluidic adaptive lens structures 100,110, 120, and other arrangements of these and other fluidic adaptive lens structures are intended to be encompassed within the present invention.

[0068] Turning to Fig. 15, performance characteristics of a functional fluidic lens optical zoom system designed and fabricated according to the process discussed above with reference to Fig. 9 are shown. The system employs water as the high index medium, and has a 20 mm aperture and an image distance of 50 mm. As shown , at an image distance of 50 mm, the ratio of the maximal to minimal magnification factor is 4.6 and 4.2 for object distances of 250mm and 1000 mm, respectively. This yields a zoom ratio of greater than 3.

[0069] More generally, to estimate the zoom ratio of the fluidic zoom lens, one can calculate zoom lenses with 3 mm and 1 mm apertures assuming water (n=1.333) as

the high index medium and air as the low index medium. For a 3mm aperture zoom lens with a lens distance of 8 mm and an image distance of 5 mm, one obtains a zoom ratio greater than 4:1. Such a zoom lens has a maximal field of view (FoV) of around 45 degrees. For a 1 mm aperture zoom lens with a lens distance of 8 mm and an image distance of 1.5 mm, one obtains a zoom ratio greater than 5: 1. The maximal field of view for such a zoom lens is about 17 degrees. If desired, one can obtain a zoom ratio greater than 10: 1 at the expense of the field of view assuming a lens distance of 8 mm and an image distance of 5 mm.

[0070] Although the fabrication process shown with reference to Fig. 9 is not directly applicable to the construction of the lens structures 100,110 and 120 shown in Figs. 10-11, a number of fabrication processes for such lens structures are possible. For example, one exemplary process for constructing the lens structures 100 could employ the following steps. In a first step, cavities are formed on two separate pieces of transparent substrate. The diameter of the cavities can vary from a few hundred micrometers to a few centimeters depending on the application, and the thickness (depth) of the cavities could be in the range of a few hundred micrometers to a few millimeters. In a second step, a thin polymer membrane is formed. The membrane thickness is in the range of tens of micrometers to 100 μm and the membrane behaves elastically under stress. The membrane will be used as a flexible diaphragm separating the cavities to be filled with media of different indices of refraction.

[0071] Next, in a third step, opposite sides of the polymer membrane formed in the second step are respectively bonded to the respective cavities formed in the first step to form two closed cavities, one on either side of the membrane. Then, in a fourth step, holes are formed in the side walls of each of the cavities to provide inlets/outlets for the fluidic media (in some embodiments, a given hole or channel can act as both an inlet and an outlet, while in other embodiments, dedicated holes/channels are provided specifically as either inlets or outlets). Then, in a fifth step, the inlets and outlets are coupled to one or more fluid reservoirs (typically, in this case, first and second reservoirs for first and second fluidic media). Further, in a sixth step, one or more actuators are incorporated to control the flow of the fluidic

media into and out of the cavities (e.g., by varying the pressures of the fluidic media). These actuators can take on any of a number of forms including, for example, fluidic micro pumps, piezoelectric actuators, micro-electro-mechanic-system (MEMS) actuators, or teflon-coated set screws to control and set the pressure of each fluid chamber.

[0072] Next, in a seventh step, two fluidic media of different refractive indices are provided into the respective cavities. For example, one of the media can be water having an index of 1.3 and the other medium can be oil having a refractive index of about 1.6. (In alternate embodiments, the fluidic media can have the same refractive index). This completes the construction of one of the lens structures 100. Once two of the lens structures 100 have been fabricated, the two lens structures can then be mounted to an optical medium to form the optical medium 140 between the two structures as shown in, for example, Fig. 12. As noted above, the optical medium can be, for example, a solid transparent substrate of certain thickness (e.g. a glass wafer or a polymer substrate) to form one of the two-lens optical zoom lens systems 122,124 of Figs. 12(a) and 12(b).

[0073] Other processes for fabricating the zoom lens structure 100 of Fig. 10 as well as the zoom lens structures 110 and 120 of Fig. 11 are also possible, as are other processes for fabricating the two-lens optical zoom systems 122-138 of Figs. 12-14. Once constructed, the entire optical zoom systems can take the form of cylindrical tubes of a few millimeters in diameter and about one centimeter long. Such devices can be conveniently attached to many handheld or pocket-sized devices. To the extent that a zoom lens can be made into a compact attachment retrofit to commercial optical systems, many additional products such as eyeglasses or goggles with zooming functions are possible.

[0074] It is specifically intended that the present invention not be limited to the embodiments and illustrations contained herein, but include modified forms of those embodiments including portions of the embodiments and combinations of elements of different embodiments as come within the scope of the following claims.

CLAIMS

WE CLAIM:

1. A lens comprising:

a first partition that is flexible and optically transparent;

a second partition that is coupled to the first partition, wherein at least a portion of the second partition is optically transparent, and wherein a first cavity is formed in between the first partition and the second partition;

a first fluidic medium positioned within the cavity, the fluidic medium also being optically transparent; and

a first device capable of controlling a parameter of the fluidic medium,

wherein when the parameter of the fluidic medium changes, the first partition flexes and an optical property of the lens is varied.

2. The lens of claim 1, wherein the first partition is a flexible membrane formed from at least one of a thin plastic polymer and another flexible, optically transparent material.

3. The lens of claim 1, wherein the second partition is a rigid partition formed from at least one of a plastic and another material that is at least partly optically transparent.

4. The lens of claim 3, wherein the second partition includes at least one channel allowing for the fluidic material to at least one of enter and exit the cavity.

5. The lens of claim 3, wherein the second partition includes a first portion that extends substantially parallel to the first partition when the first partition is in an unflexed position and also includes second and third portions that extend substantially perpendicularly to the first portion.

6. The lens of claim 1, wherein a first side of the flexible membrane is adjacent to the first fluidic medium and a second side of the flexible membrane is adjacent to a second fludic medium.

7. The lens of claim 6, wherein the second fluidic medium is air of the atmosphere.

8. The lens of claim 6, further comprising a third partition that is coupled to the first partition, wherein at least a portion of the third partition is optically transparent, wherein a second cavity is formed in between the third partition and the second partition, wherein the first partition extends substantially in between the second and third partitions, and wherein the second fluidic medium is positioned within the second cavity.

9. The lens of claim 8, further comprising a second device capable of controlling a second parameter of the second fluidic medium, and wherein each of the first and second devices includes at least one actuator selected from the group consisting of a small-mounted pump, a piezoelectric actuator, a microelectromechanical system (MEMS) actuator, and a Teflon-coated screw for controlling and setting fluidic pressure and volume.

10. The lens of claim 8, wherein the third partition is rigid, and the second and third partitions substantially surround the first partition so that the first partition is shielded from an outside environment.

11. The lens of claim 8, further comprising a fourth partition that is coupled to the third partition, wherein at least a portion of the fourth partition is optically transparent, wherein a third cavity is formed in between the third partition and the fourth partition, wherein the third partition extends substantially in between the first and fourth partitions, and wherein at least one of the first fluidic medium, the second fluidic medium and a third fluidic medium is positioned within the third cavity.

12. The lens of claim 11, wherein the third partition is flexible, and wherein flexing of the first and third partitions depends upon relative pressures of the fluidic media within the first, second and third cavities..

13. The lens of claim 1, wherein the lens is configured to be mounted within at least one of a pair of eyeglasses, a camera, microscope, a video monitor, a video recorder, a copy machine, a scanner, a zoom lens system, a cell phone, a personal digital assistant, a computer, and a magnifying glass.

14. A multi-lens apparatus comprising:

a first fluidic adaptive lens;

a second fluidic adaptive lens; and

an intermediate structure coupling the first and second fluidic adaptive lenses, wherein the intermediate structure is at least partly optically transparent.

15. The multi-lens apparatus of claim 14, wherein each of the first and second fluidic adaptive lenses includes at least one flexible membrane and at least one rigid partition surface that together define at least one cavity within which is at least one fluidic medium.

16. The multi-lens apparatus of claim 15, wherein each of the first and second fluidic adaptive lenses includes either one or two flexible membranes.

17. The multi-lens apparatus of claim 14, wherein at least one parameter of each of the at least one fluidic medium is controllable by at least one of means for providing fluid flow and means for varying fluid pressure.

18. The multi-lens apparatus of claim 17, wherein by controlling the at least one parameter, a flexure of at least one membrane is affected that affects at least one of a lens focal distance and a lens orientation, and wherein the multi-lens system is capable of operating as a zoom lens system.

19. A method of fabricating a fluidic adaptive lens device, the method comprising:

providing a structure having an open-ended cavity formed therewithin;

affixing a flexible membrane to the structure in a manner sealing the cavity except insofar as at least one channel within at least one of the structure and the membrane allows for communication of a fluid with respect to the cavity,

wherein the cavity is capable of being filled with the fluid so that the structure, flexible membrane and fluid interact to form a first lens device.

20. The method of claim 19, further comprising:

affixing the structure to a first side of an intermediate substrate; and

affixing a second lens device to a second side of the intermediate substrate,

wherein the first and second lens devices and the intermediate substrate can be operated together as a zoom lens system.

ABSTRACT

A fluidic adaptive lens, a multi-lens apparatus employing the fluidic adaptive lens, and a method of fabricating a fluidic adaptive lens are disclosed. The lens includes a first partition that is flexible and optically transparent, and a second partition that is coupled to the first partition, where at least a portion of the second partition is optically transparent, and where a first cavity is formed in between the first partition and the second partition. The lens further includes a first fluidic medium positioned within the cavity, the fluidic medium also being optically transparent; and a first device capable of controlling a parameter of the fluidic medium, where when the parameter of the fluidic medium changes, the first partition flexes and an optical property of the lens is varied.

Lens Type Tunability in Fluidic Adaptive Lens

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Robust and thermally stable fluidic adaptive lenses with wide-range focal length tunability have been demonstrated by the authors[1,2]. Such adaptive lenses not only eliminate the mechanical moving parts in optical systems, but also simplify the optic design, improve optical performance, and integrate new functions into current optical systems. To help create a paradigm shift in the design and realization of optical systems, further work is reported to extend the tunability of the fluidic adaptive lenses so that not only their properties but also their lens types can be tuned on demand. Essentially, by adjusting the fluidic pressure, one can turn a fluidic lens into convex, concave, convex-concave, convex-plano, and many different types of simple and compound lenses of desired properties. The realization of fluidic lenses is inspired by biological lenses of animal eyes.

For a demonstration of a broader concept of tunable lens types, we formed a fluidic adaptive lens consisting of two back-to-back polydimethylsiloxane (PDMS) fluidic chambers each covered by a thin (60 μm) PDMS membrane. A thin glass slide (150 μm) was sandwiched between the lens chambers via oxygen plasma activated PDMS/glass bonding. The lens aperture is 20mm. These two lens chambers are connected to a hand-held fluidic system through the fluidic inlet and outlet. By dynamically controlling the fluidic pressure in these two lens chambers respectively, plano-convex, plano-concave, convex-concave, biconvex, and biconcave lens types can be achieved with wide focal length tunability for each and every lens type. Figure 1 shows the focal length tunability by fluidic pressure for plano-convex and plano-concave lenses. Figure 2 shows the focal length tunability for convex-convex and convex-concave lenses. To obtain the curves in Figure 2, the pressure in one of the lens chambers was fixed at 6931.6 Pascal while the fluidic pressure in the other lens chamber was varied. Figure 3 shows the focal length tunability for biconvex and biconcave lenses. Overall the shortest positive and negative focal lengthes achieved in this double-chamber fluidic adaptive lens are 21 mm and –18 mm, respectively. For a 20 mm lens aperture, these correspond to an F number of 1.05 and –0.9, respectively. Figure 4 is one of the resolution measurement pictures of the fluidic adaptive lens. It shows that the fluidic adaptive lens has a high resolution of 40 lp/mm (line pairs per millimeter) and good image quality.

In summary, we have demonstrated a fluidic adaptive lens with not only wide focal length adjustability but also lens type tunability. The versatile bio-inspired fluidic adaptive lens could lead to significant reduction in the size, weight, cost, and complexity of optical systems, major savings in lens inventory, and much extended functionality that can be incorporated into the systems. Therefore, the technology has the potential to create a paradigm shift in the design and realization of optical systems.

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Reference:

1. D. Y. Zhang, V. Lien, Y. Berdichevsky, J. Choi, and Y. H. Lo, "Fluidic adaptive lens with high focal length tunability", Applied Physics Letters Vol. 82, No. 19, 3171-3172 (2003)
2. D. Y. Zhang, Y. H. Lo, "Focal Length Tunable Fluidic Adaptive Lens", Proceeding of Conference on Lasers and Electro-Optics/Quantum Electronics and Laser Science Conference, June 1-6, 2003, Baltimore, Maryland, USA

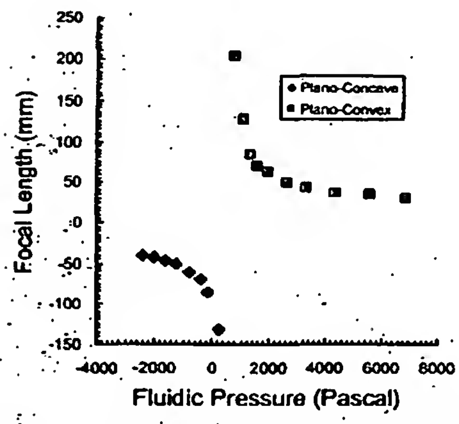

Figure 1. Focal length tunability by fluidic pressure in a fluidic adaptive lens with plano-convex and plano-concave lens types.

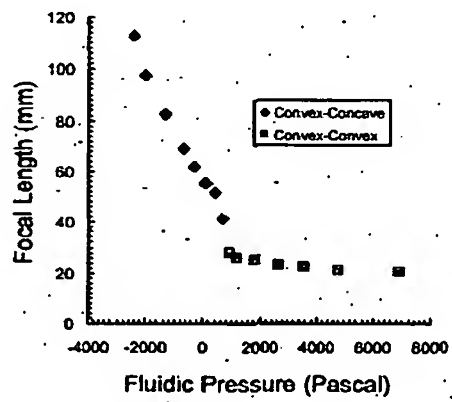

Figure 2. Focal length tunability by fluidic pressure in a fluidic adaptive lens with convex-convex and convex-concave lens types.

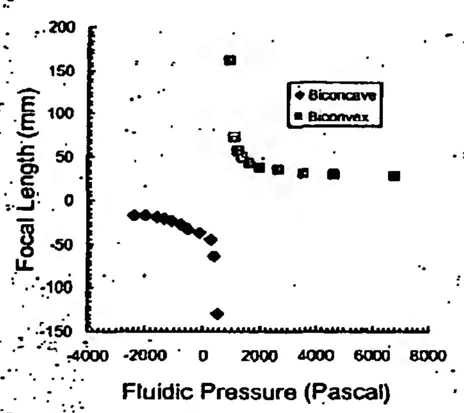

Figure 3. Focal length tunability by fluidic pressure in a fluidic adaptive lens with biconvex and biconcave lens types.

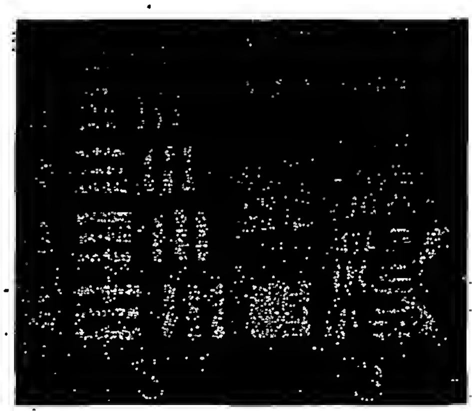

Figure 4. Resolution measurement picture using the negative USAF standard for an adaptive fluidic lens having a focal length of 43mm

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Fluidic adaptive lens with high focal length tunability

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Fluidic adaptive lenses with an adjustable focal length over a wide range were demonstrated in this letter. The focal length adjustment was achieved by changing the shape of the fluidic lens without any mechanical moving parts. The shortest focal length demonstrated in such devices is 41 mm, which corresponds to a large numerical aperture of 0.24 and a small F number of 2.05. The highest resolution measured using a positive standard is 25.39 lp/mm in this fluidic adaptive lens. © *2003 American Institute of Physics.* [DOI: 10.1063/1.1573337]

Most of the conventional optical systems such as cameras and microscopes are made of solid materials such as glass, crystals, and plastics. These systems are bulky and complicated because they require mechanical moving parts to tune and adjust[1] the optical components. In contrast, biological vision systems are much more compact because they achieve tuning and adjustment by changing the shape or refractive index of their lens systems.[2] However, these biological systems, although being very advanced in optical design, are not robust and stable enough for many applications. For this reason, adaptive lenses that can adjust their focal length by changing the shape or refractive index without moving parts and yet are robust and thermally stable are particularly attractive. The tunability of adaptive lenses is desirable for both civilian and military applications such as optical recording systems and surveillance and inspection systems.[3] In this letter, we demonstrate a fluidic adaptive lens inspired by animal eyes' crystalline lenses that can be deformed by muscles to adjust their focal length.

Figure 1 shows the picture of the fluidic adaptive lens. The fluidic adaptive lens consists of a polydimethylsiloxane (PDMS) fluidic chamber covered by a thin (60 μm) PDMS membrane and bonded to a thin (150 μm) handling glass slide. The PDMS chamber and membrane were fabricated separately using soft lithography process[4] and then bonded together using the oxygen plasma bonding technology[5] to form the body of the lens. After the structure had been formed, the bottom of the fluidic chamber was bonded to a thin glass slice for easy handling using again oxygen plasma activated bonding technique. The diameter of the lens is 20 mm. The lens chamber is connected to a syringe pump through the fluidic inlet. When pressure is applied by the syringe pump to inject fluid into the lens chamber, the focal length of the lens changes because of the elastic deformation of the PDMS membrane.

Table I shows the change of the focal length, resolution, and numerical aperture (NA) with the fluidic pressure in the lens. It is clearly demonstrated that the focal length and the NA can be dynamically controlled through the fluidic pressure over a very wide range. According to the experimental results, the relation between focal length and the fluidic pressure can be expressed as follows:

$$\mathrm{Ln}(f) = -0.4859\mathrm{Ln}(P) + 7.9069, \tag{1}$$

where Ln is the natural log function and the focal length (f) and applied fluidic pressure (P) are in millimeters and pascals, respectively. The R-squared value for the equation is 0.9797, indicating a good fit of the equation to the real situation Fig. 2 shows the measured results of the dependence of the focal length on the fluidic pressure. The shortest focal length achieved in this device is 41 mm, corresponding to the smallest F number of 2.05. This F number is comparable to that of human eyes with wide open pupil.[2] Figure 3 shows the change of NA with the fluidic pressure in this fluidic adaptive lens. The largest NA in this adaptive lens is 0.24. We also used the positive standard to measure lens resolution. Figure 4 is the result of the measurement. It shows that the best resolution of this fluidic adaptive lens is 25.39 lp/mm in both horizontal and perpendicular directions. Figure 5 shows one of the pictures of the resolution measurement using positive standard. Work is going on to introduce index gradient to the fluidic lens to reduce the aberration inherent to spherical lenses.

In summary, we demonstrated a fluidic adaptive lens with an adjustable focal length over a very wide range. The focal length can be dynamically controlled through changing

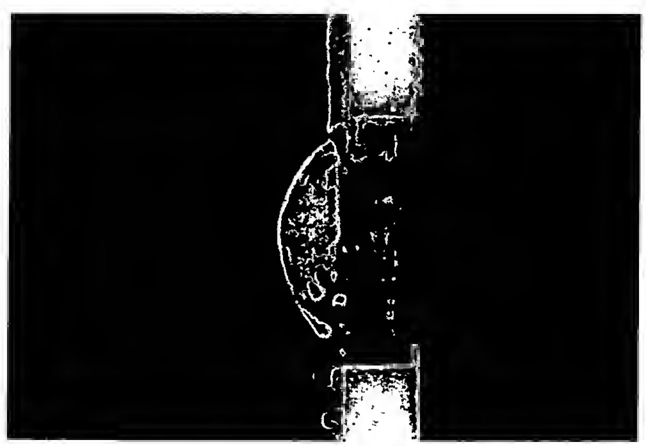

FIG. 1. Photography of a 2 cm aperture fluidic adaptive lens.

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TABLE I. Focal length, resolution, and NA in fluidic adaptive lens.

Fluidic pressure (Pa)	Focal length (mm)	NA	Resolution	
			Horizontal	Perpendicular
399.9	172	0.058	8.98	10.10
533.2	124	0.080	11.30	14.30
799.8	95	0.10	17.95	17.95
1199.7	84	0.12	20.16	20.16
1732.9	70	0.14	22.62	22.62
2266.1	62	0.16	25.39	25.39
2799.3	56	0.18	20.16	20.16
3599.1	52	0.19	20.16	20.16
4398.9	48	0.20	17.95	17.95
5065.4	44	0.22	16.00	16.00
5865.2	41	0.24	12.70	14.30

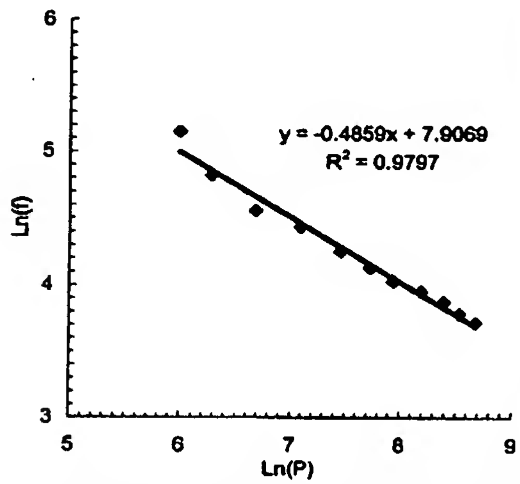

FIG. 2. Dependence of focal length on fluidic pressure in a spherical fluidic adaptive lens. The solid line is a fit of the data, indicating that the focal length is approximately proportional to the inverse square root of the pressure.

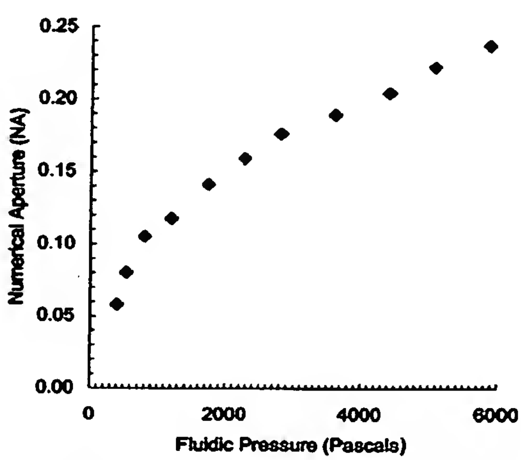

FIG. 3. Numerical aperture vs fluidic pressure in spherical fluidic adaptive lens.

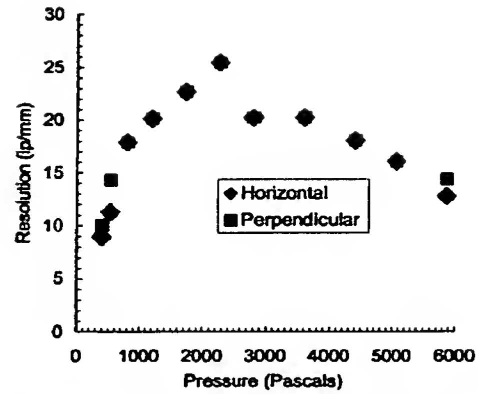

FIG. 4. Vertical and horizontal resolution with positive standard vs fluidic pressure in fluidic adaptive lens.

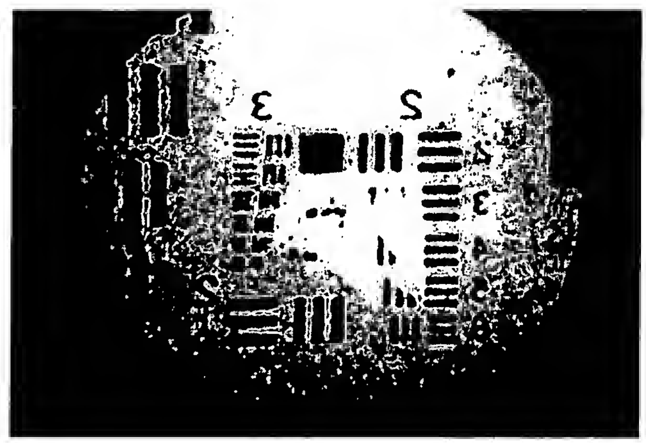

FIG. 5. A picture of resolution measurements of fluidic adaptive lenses using positive standard.

the shape of the fluidic adaptive lens without mechanical moving parts. The bio-inspired fluidic adaptive lens shows great promise for significant size, weight, cost, and complexity reduction and can become an attractive building block for high performance yet cost sensitive optical systems.

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[1] *Lens Design*, edited by M. Laikin (Marcel Dekker, New York, 2001).
[2] *Animal Eyes*, edited by M. F. Land and D. E. Nilsson (Oxford University Press, Oxford, 2002).
[3] *Adaptive Optics Engineering Handbook*, edited by R. K. Tyson (Marcel Dekker, New York, 2000).
[4] Y. Xia and G. M. Whitesides, Angew. Chem., Int. Ed. Engl. 37, 550 (1998).
[5] B. H. Jo, L. M. Van Lerberghe, K. M. Motsegood, and D. J. Beebe, J. Microelectromech. Syst. 9, 76 (2000).

High-performance fluidic adaptive lenses

De-Ying Zhang, Nicole Justis, Victor Lien, Yevgeny Berdichevsky, and Yu-Hwa Lo

High-performance fluidic lenses with an adjustable focal length spanning a very wide range (30 mm to infinite) are demonstrated. We show that the focal length, F-number, and numerical aperture can be dynamically controlled by changing the shape of the fluidic adaptive lens without moving the lens position mechanically. The shortest focal length demonstrated is less than 30 mm for a 20-mm lens aperture. The fluidic adaptive lens has a nearly perfect spherical profile and shows a resolution better than 40 line pairs/mm in a plano–convex structure and 57 line pairs/mm in a biconvex structure. © 2004 Optical Society of America

OCIS codes: 080.3630, 220.3630, 160.5470.

1. Introduction

A robust and thermally stable lens with a widely tunable focal length is desirable for applications such as optical recording, cameras, microscopes, surveillance, inspection, agile imaging, and target tracking.[1,2] Such tunable lenses eliminate the mechanical moving lenses for focal-length adjustment and therefore can significantly reduce the size and complexity of optical systems. For example, one tunable objective lens potentially provides the functions of four to five microscope objective lenses of different magnifications and numerical apertures (NAs), yielding significant cost savings and weight reduction of the system. In the most general sense, fluidic tunable lenses emulate biological lenses in animal eyes, which have been proven to be highly successful after millions of years of evolution. However, the fluidic-based tunable lenses that we fabricated are much more robust and thermally stable compared with the biological lenses. Combining the merits of both biological lenses and solid-state lenses is the guiding principle of our research on fluidic lenses, which also builds on the previous research in fluidic optics.[2–9] We have previously demonstrat such robust and thermally stable fluidic adaptive lenses with wide-range focal-length tunability.[10,11] In this paper we report further research results of fluidic adaptive lenses with a significant performance improvement and more-diversified lens structures. For a single fluidic adaptive lens, we demonstrate the shortest focal length of less than 30 mm with high resolution and low spherical aberration. The results have moved the state of the art significantly forward and, in many key aspects, are comparable to the most sophisticated biological lenses that have inspired our research.

2. Lens Fabrication and Experimental Setup

The plano–convex fluidic adaptive lens[10,11] consists of a polydimethylsiloxane (PDMS) fluidic chamber covered on either side with a thin (30–100-μm) PDMS membrane and a thin (150-μm) glass slide, whereas the biconvex fluidic adaptive lens consists of a PDMS fluidic chamber covered on both sides with 60-μm PDMS membranes. The PDMS chamber and membrane(s) were fabricated separately by a soft lithography process[12] and then bonded together by oxygen plasma surface activation.[13] The thickness of the PDMS chamber is 4 mm and the diameter of the aperture is 20 mm for both plano–convex and biconvex lenses. Deionized water was used as the medium for both types of lens. The pressure of the lens chamber was controlled by a hand-held, battery-powered fluidic system consisting of valves, a peristaltic pump, electronic control circuit, and a pressure sensor.

Figure 1 is a schematic drawing of the fluidic system for pressure control. A minipump (12 V, 35 rpm) was used to inject or withdraw fluid into or out of the lens chamber. With fluid injection, pressure to the PDMS membrane built up and the membrane was deformed elastically to a convex shape. As the

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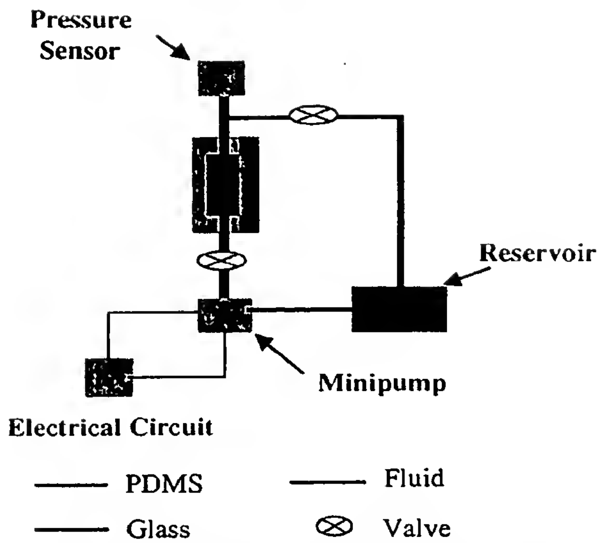


Fig. 1. Schematic drawing of the fluidic system for pressure control.

pressure increased, the radius of curvature of the elastic PDMS film decreased, causing the reduction of the focal distance of the lens. The fluidic pressure was measured with a pressure sensor connected to the lens outlet. Furthermore, the fluidic pressure was controlled through two two-way valves, connected to the fluidic inlet and outlet, respectively.

3. Tunability in Optical Parameters

Using this fluidic system, we measured the tunability of the focal length, F-number, and NA by fluidic pressure. A He–Ne 632.8-nm laser was used as the light source for these measurements.

Figure 2 shows the relationship between the focal length and the fluidic pressure in 20-mm-diameter plano–convex fluidic lenses with a PDMS membrane thickness of 30, 60, and 100 μm, respectively. The minimal focal lengths achieved are 27.81, 28.85, and 31.97 mm, respectively, with the shortest focal distance obtained from the lens of the thinnest membrane. The same trend and similar tuning characteristics were also found in biconvex lenses. Figure 3 shows a comparison of focal-length tunability between plano–convex and biconvex lenses, both having a membrane thickness of 60 μm. Clearly the biconvex lens has a smaller minimal focal length (26.24 mm) than the plano–convex lens (28.85 mm), and a lower fluidic pressure is needed for biconvex lenses to achieve the same focal distance as the plano–convex lenses. In either lens structure, both the tuning range and the achievable minimal focal distance are significantly better than the best reported values of adaptive lenses having similar lens apertures. A short focal distance can result in a wide field of view, large NA, and strong focal power,

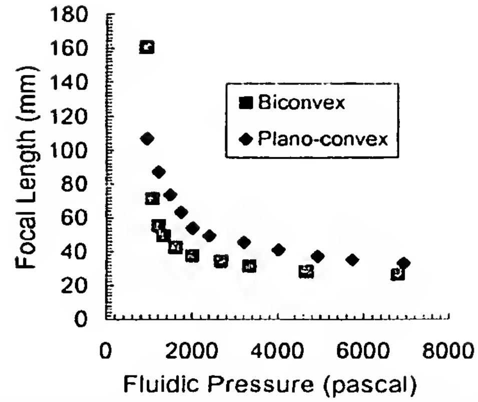


Fig. 3. Focal-length tunability with fluidic pressure in plano–convex and biconvex fluidic adaptive lenses with a PDMS membrane thickness of 60 μm.

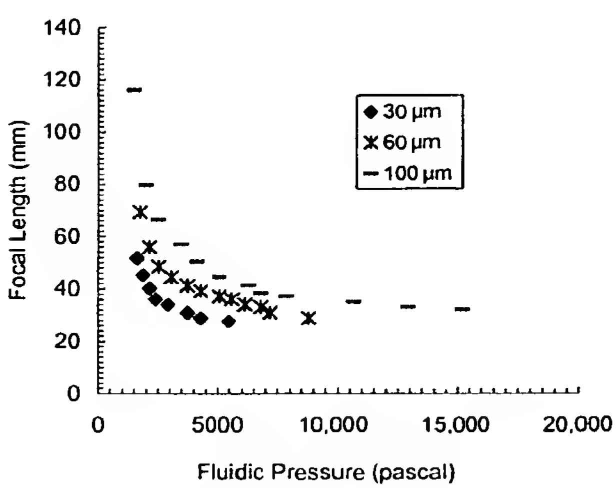


Fig. 2. Dependence of focal length on fluidic pressure in plano–convex fluidic adaptive lenses.

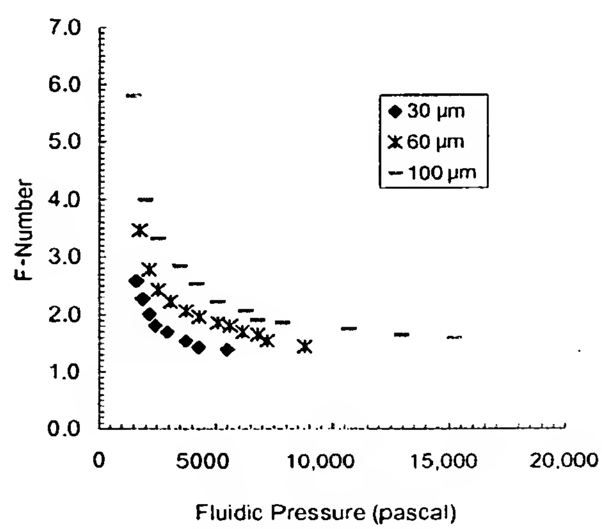


Fig. 4. Dependence of F-number on fluidic pressure in plano–convex fluidic adaptive lenses.

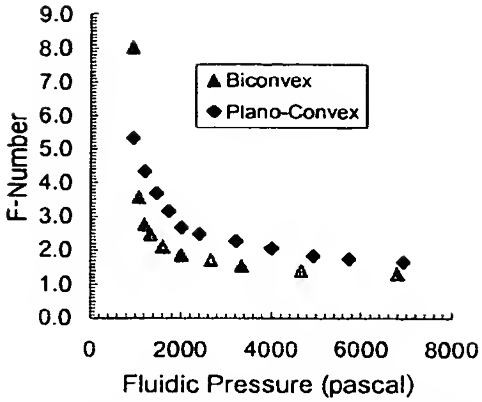


Fig. 5. Dependence of F-number on fluidic pressure in plano–convex and biconvex fluidic adaptive lenses with a 60-μm membrane.

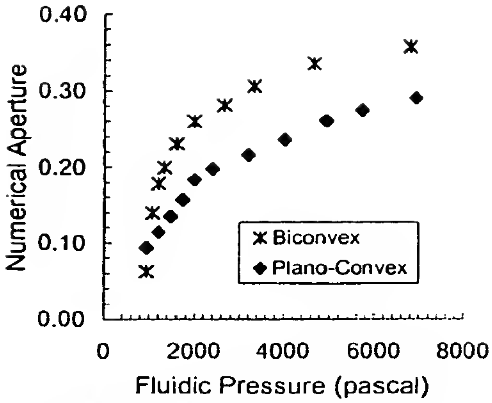


Fig. 7. Dependence of the NA on fluidic pressure in plano–convex and biconvex fluidic adaptive lenses.

all being important figures of merit for various optical systems. Furthermore, the ability to dynamically control the focal length over a very wide range (30 mm to infinite) by fluidic pressure was clearly demonstrated.

Figures 4 and 5 show the dependence of the F-number on fluidic pressure, and Figs. 6 and 7 show the relation between NA and fluidic pressure. Clearly both the F-number and the NA can also be dynamically controlled by the fluidic pressure over a very wide range. Compared with the plano–convex fluidic lens, the biconvex lens has a shorter focal length, a smaller F-number, and a larger NA.

4. Optical Performance

To characterize the quality of the fluidic adaptive lenses, we measured their resolution and distortion.

Figures 8–10 show the resolution measurements of plano–convex and biconvex fluidic adaptive lenses, performed with a 632.8-nm He–Ne laser source with positive and negative U.S. Air Force resolution targets. For all these measurements, the image plane was at a fixed position of 635 mm behind the lenses. Figure 8 shows the resolution measurements of plano–convex lenses with 30-, 60-, and 100-μm membranes; and Fig. 9 shows the resolution measurements of plano–convex and biconvex lenses with 60-μm membranes. Figure 10 is one of the pictures from the resolution measurements. These studies suggest that there exists no clear dependence of the image quality on the membrane thickness of the lenses and that the fluidic adaptive biconvex lens has, in general, a higher image resolution than the plano–convex lens made by the same process. For biconvex fluidic adaptive lenses, a maximum resolution of 57 line pairs/mm was demonstrated. For all the fluidic adaptive lens structures studied in our research, the maximum resolution is better than 40 line pairs/mm.

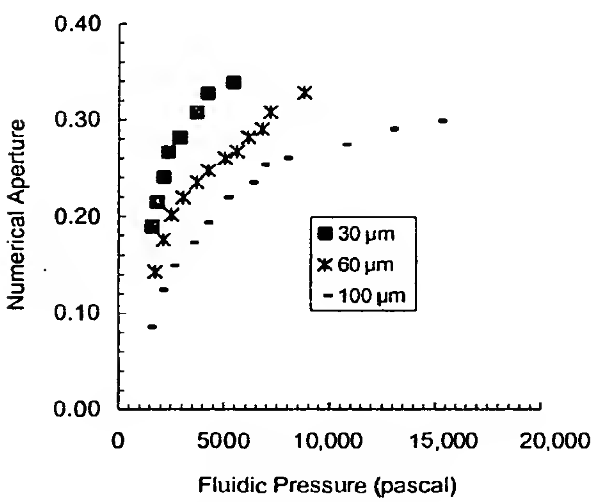


Fig. 6. Dependence of the NA on fluidic pressure in plano–convex fluidic adaptive lenses.

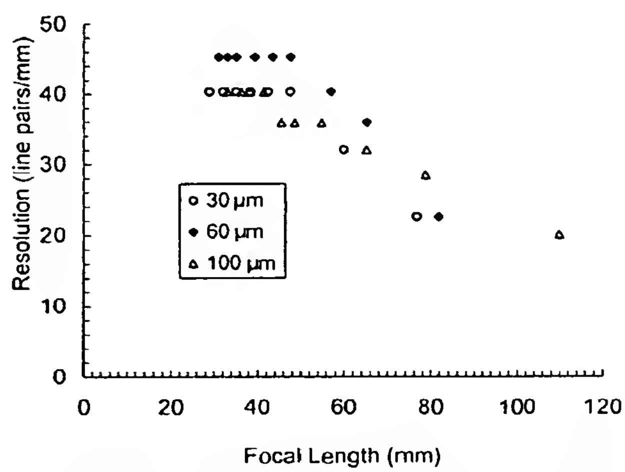


Fig. 8. Resolution versus focal length for plano–convex fluidic adaptive lenses measured with a positive U.S. Air Force test pattern.

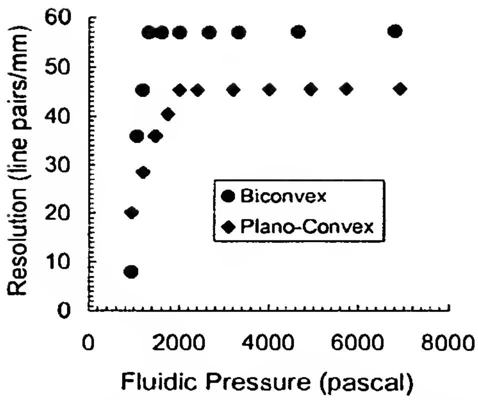
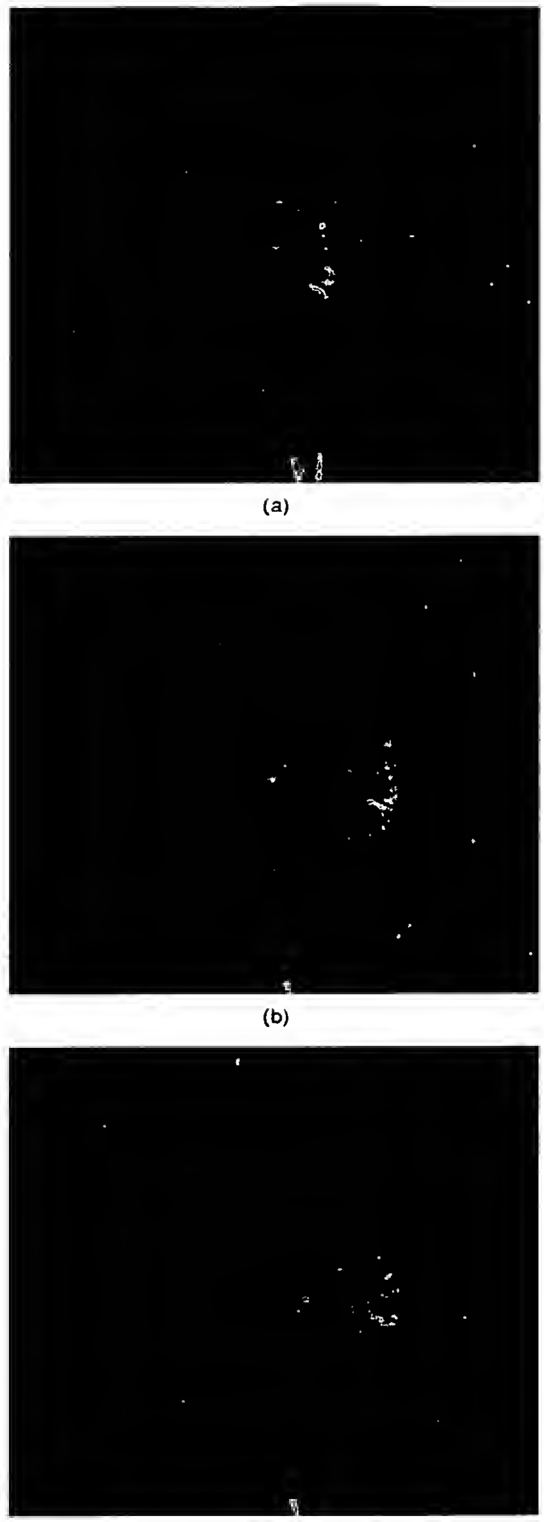


Fig. 9. Resolution versus fluidic pressure measured with a negative U.S. Air Force test pattern in plano–convex and biconvex fluidic adaptive lenses with a 60-μm membrane.

However, we could see that the resolution was reduced rather rapidly when the focal length was greater than 70 mm where the chamber pressure was low. This reduction in image resolution is attributed in part to the lower magnification factor due to the increasing focal length because we fixed the distance of the image plane throughout the measurements. The other factor causing the reduced resolution might be the gravity effect on the fluid in the lens chamber. At a long focal distance or low fluidic pressure, the weight of the fluid might become a nonnegligible perturbation that causes nonuniform surface tension in the membrane and creates an asymmetric lens shape with degraded resolution.[8] The gravity effect of the fluid diminishes rapidly as the fluidic pressure and surface tension of the lens membrane increase.

In addition to image resolution, we studied

Fig. 10. Picture of resolution measurement with a negative U.S. Air Force standard on a fluidic adaptive lens at a 43-mm focal length.



(a)

(b)

(c)

Fig. 11. Photographs for image distortion measurement on a 60-μm membrane adaptive lens at (a) 51-, (b) 43-, (c) 34-mm focal lengths. The dot diameter is 1.00 mm and the dot center-to-center spacing is 2.00 mm in the grid distortion target.

Table 1. Profile of the Fluidic Adaptive Lens with a 30-μm Membrane

Fluidic Pressure (pascal)	Radius of Curvature (mm)	Deviation from Ideal Spherical Surface	
		Absolute Value (μm)	Relative Value (%)
2932.6	16.027	25.4	0.16
3199.2	14.529	50.8	0.35
3332.5	13.919	38.1	0.27

aberration-induced image distortion for plano–convex fluidic adaptive lenses with a 60-μm membrane using a He–Ne laser and a grid distortion target with a 1.0-mm dot diameter and 2.0-mm dot spacing. The image plane was 635 mm behind the lens. Figures 11(a)–11(c) show the photographs for the image distortion study at three different focal lengths: 51, 43, and 34 mm, respectively. We found that the image distortion is reduced as the focal length decreases, which provides further evidence that the influence of the gravity effect is reduced and finally becomes negligible with increased fluidic pressure.

We also used an optical comparator to measure the surface profiles of fluidic adaptive lenses. Table 1 summarizes the measurement results for a 30-μm membrane plano–convex fluidic adaptive lens. The results show that the lens profile is less than 0.35% different from a spherical surface and the maximal deviation occurs near the center area, which appears to be flatter than spherical.

5. Conclusion

In summary, we have demonstrated plano–convex and biconvex fluidic adaptive lenses where the focal length, *F*-number, and NA can all be tuned dynamically by means of changing the lens shape by fluidic pressure. Tuning without physically switching the hardware or employing mechanical moving parts is the key attribute of the design. A focal length less than 30 mm has been demonstrated, which to our knowledge is the shortest value ever reported for a tunable lens of comparable size (i.e., 20-mm aperture). The short focal length gives rise to a large NA, a wide field of view, and strong focal power, all important characteristics for various applications. The fluidic adaptive lenses have a nearly perfect spherical shape and produce a resolution better than 40 line pairs/mm in a plano–convex structure and 57 line pairs/mm in a biconvex structure. As demonstrated, the fluidic adaptive lens that functions similarly in many ways to biological lenses shows promise for significant size, weight, cost, and complexity reduction. It can become an attractive building block for high-performance yet cost-sensitive optical systems.

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References

1. B. Javidi, ed. *Smart Imaging Systems,* Vol. 91 of the SPIE Press Monographs (SPIE, Bellingham, Wash., 2001).
2. R. K. Tyson, ed. *Adaptive Optics Engineering Handbook* (Marcel Dekker, New York, 2000).
3. A. F. Naumov and G. D. Love, "Control optimization of spherical modal liquid crystal lenses," Opt. Exp. **4,** 344–352 (1999), http://www.opticsexpress.org.
4. T. Shirai, T. H. Barnes, and T. G. Haskell, "Real-time restoration of a blurred image with a liquid-crystal adaptive-optics system based on all-optical feedback interferometry," Opt. Commun. **188,** 275–282 (2001).
5. G. Vdovin, "Quick focusing of imaging optics using micromachined adaptive mirrors," Opt. Commun. **140,** 187–190 (1997).
6. B. M. Wright, "Improvements in or relating to variable focus lenses," English patent 1,209,234 (11 March, 1968).
7. G. C. Knollman, J. L. S. Bellin, and J. L. Weaver, "Variable-focus liquid-filled hydroacoustic lens," J. Acoust. Soc. Am. **49,** 253–261 (1970).
8. N. Sugiura and S. Morita, "Variable-focus liquid-filled optical lens," Appl. Opt. 32, 4181–4186 (1993).
9. A. H. Rawicz and I. Mikhailenko, "Modeling a variable-focus liquid-filled optical lens," Appl. Opt. **35,** 1587–1589 (1996).
10. D. Y. Zhang, V. Lien, Y. Berdichevsky, J. Choi, and Y. H. Lo, "Fluidic adaptive lens with high focal length tunability," Appl. Phys. Lett. 82, 3171–3172 (2003).
11. D. Y. Zhang and Y. H. Lo, "Focal length tunable fluidic adaptive lens," presented at the Conference on Lasers and Electro-Optics/Quantum Electronics and Laser Science Conference, Baltimore, Md., 1–6 June 2003.
12. Y. Xia and G. M. Whitesides, "Soft lithography," Angew. Chem. Int. Ed. Engl. **37,** 550–575 (1998).
13. B. H. Jo, L. M. Van Lerberghe, K. M. Motsegood, and D. J. Beebe, "Three-dimensional micro-channel fabrication in polydimethylsiloxane (PDMS) elsatomer," J. Microelectromech. Syst. **9,** 76–81 (2000).

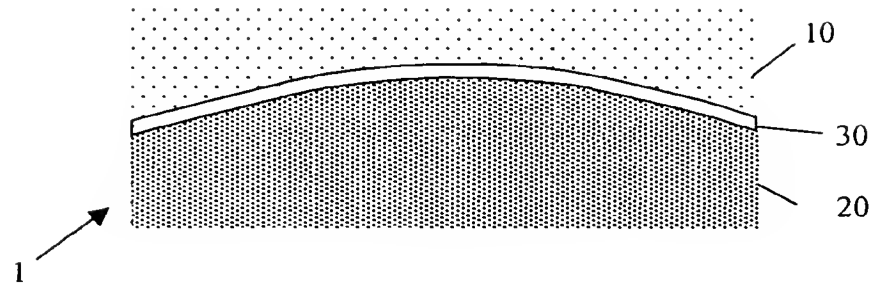

Fig. 1

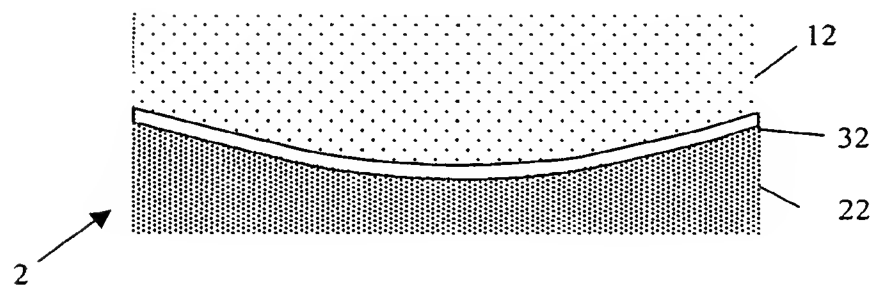

Fig. 2

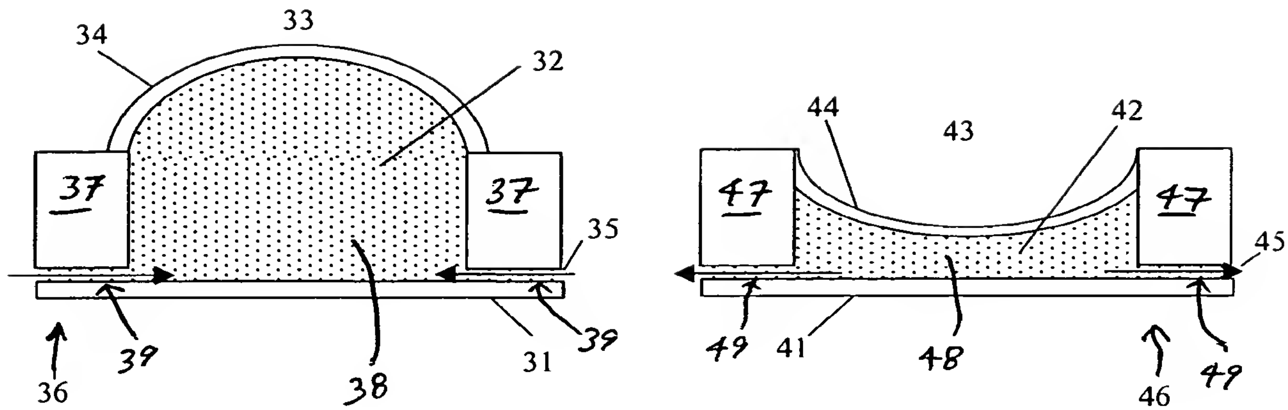

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Fig. 3

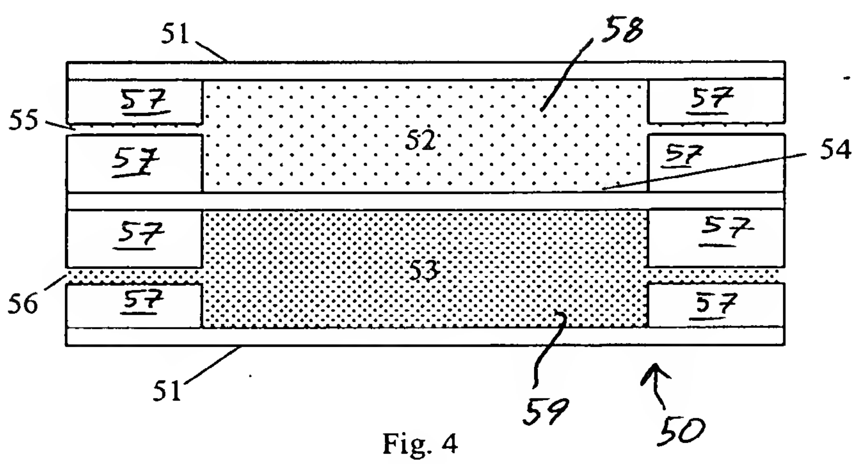

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Fig. 4

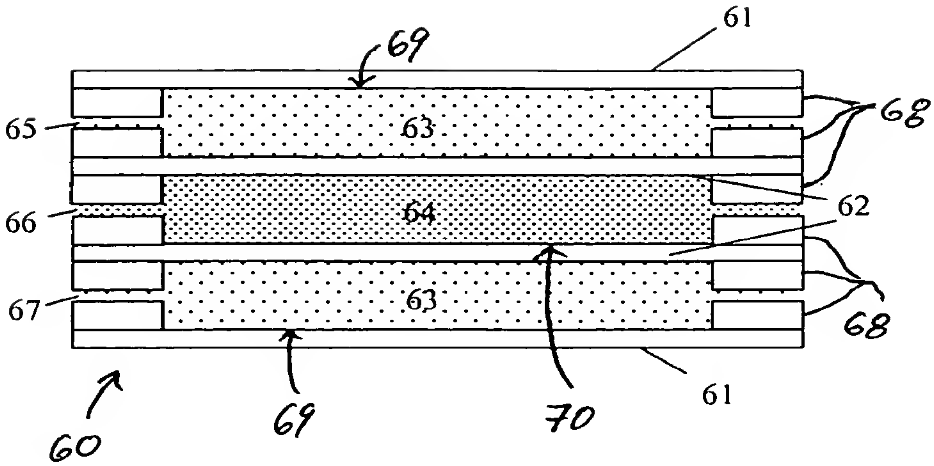
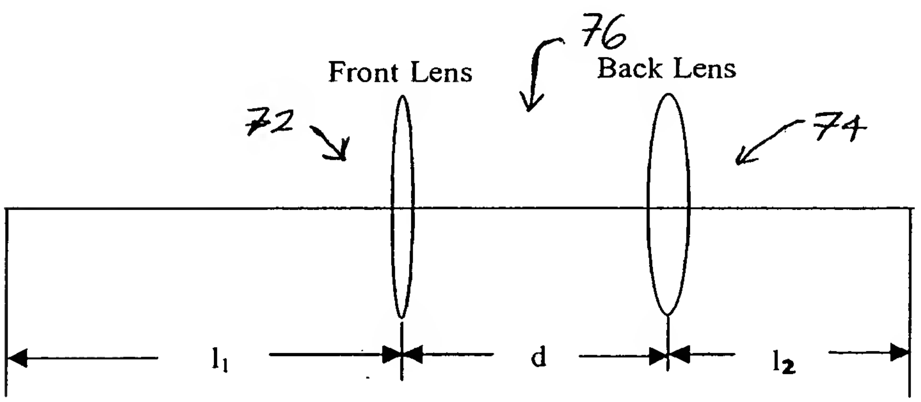


Fig. 5



l_1: object distance,
l_2: image plane distance,
d: lens spacing,
f_1: focal distance of the front (object side) lens,
f_2: focal distance of the back (image side) lens,
$\Phi_1 = 1/f_1$,
$\Phi_2 = 1/f_2$,
$\Phi_T = 1/f$: power of the zoom lens system,
ZR (zoom ratio)

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Fig. 6

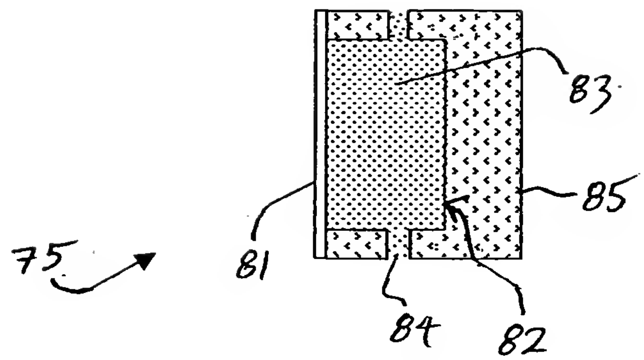
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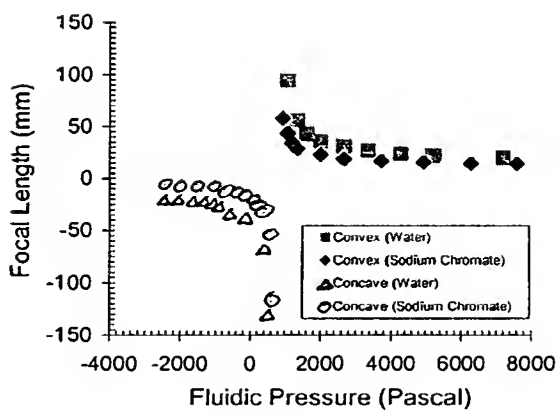
Fig. 7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-150
Focal Length (mm)
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Convex (Sodium Chromate)
Concave (Water)
Concave (Sodium Chromate)
-4000 -2000 0 2000 4000 6000 8000
Fluidic Pressure (Pascal)

Fig. 8

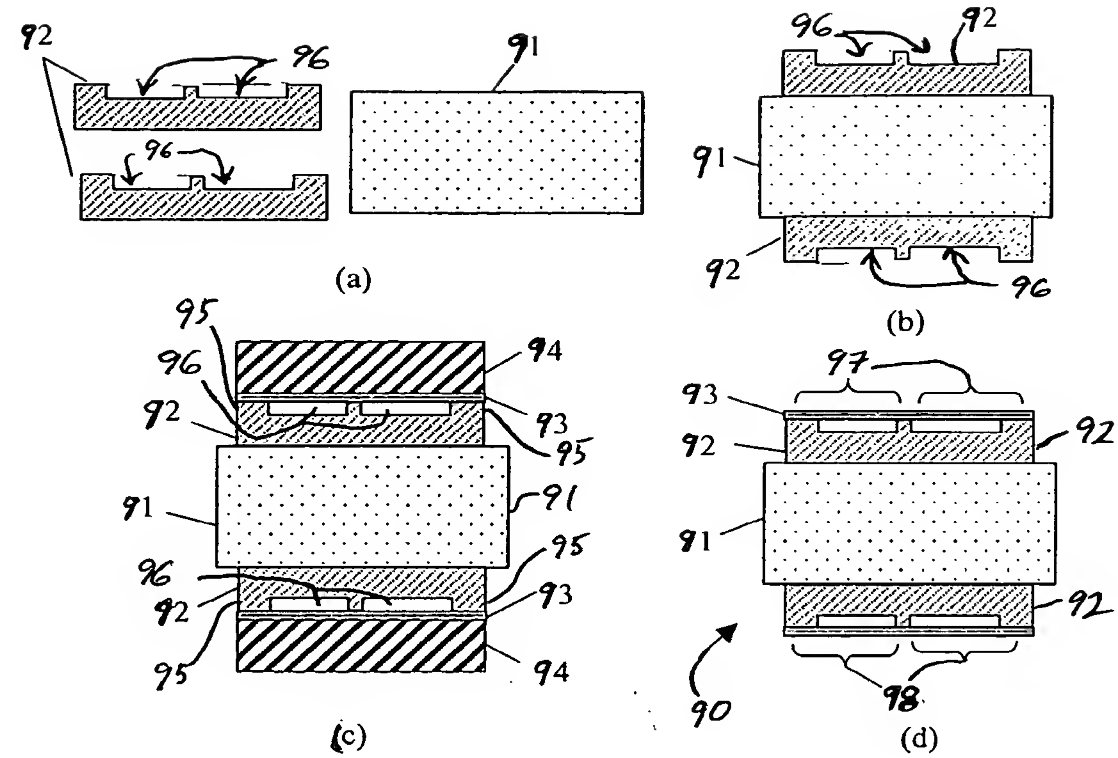


Fig. 9

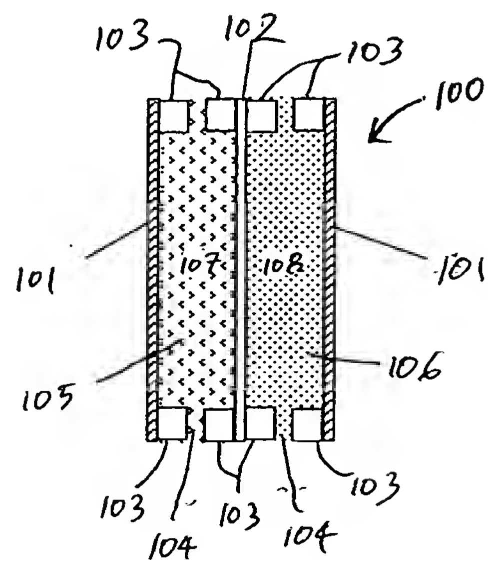
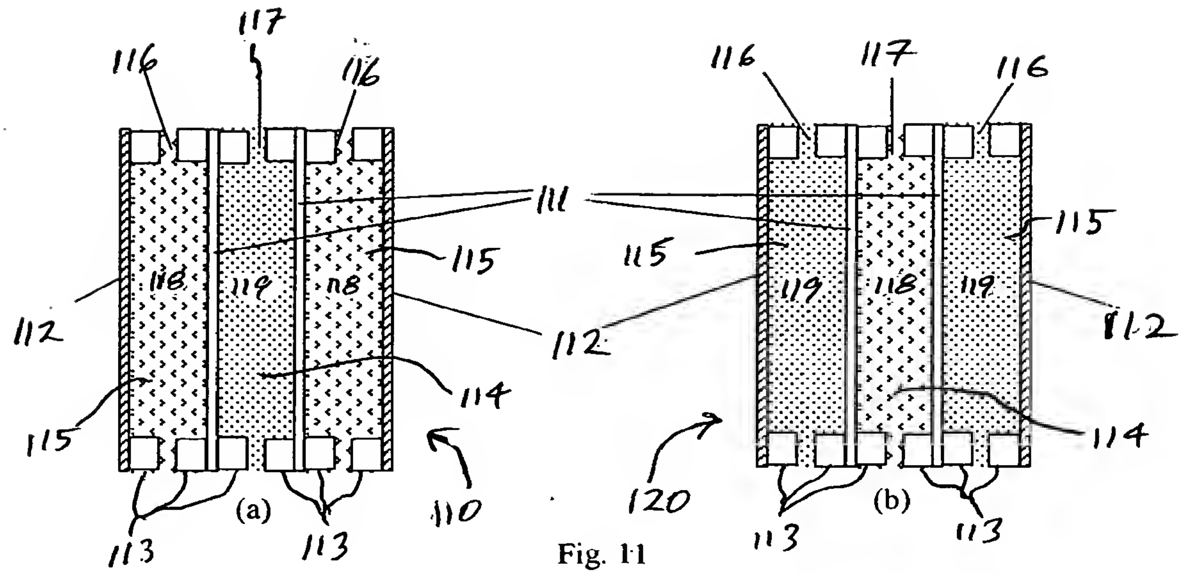
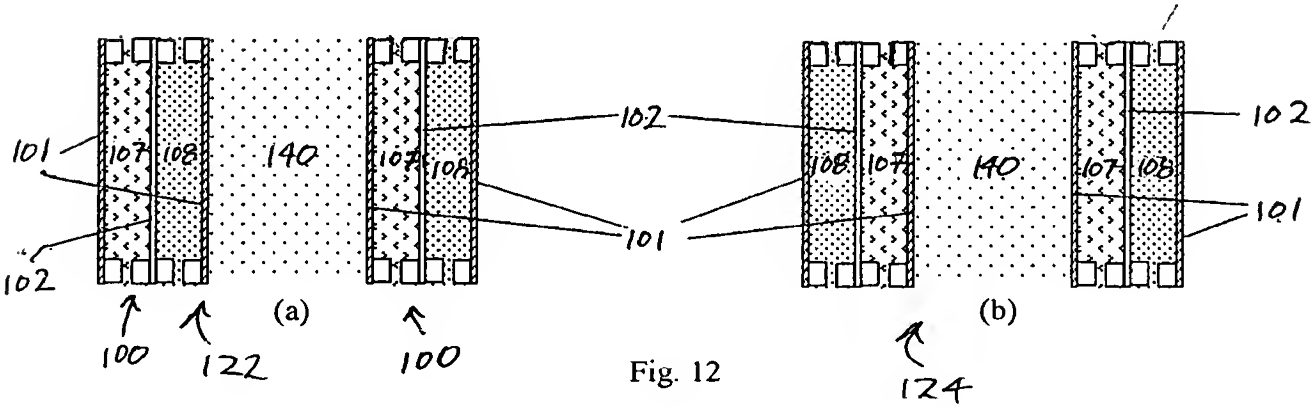


Fig. 10


117
116
116
116
117
116
111
115
115
118
119
118
119
118
119
112
112
112
112
114
114
115
(a)
(b)
110
120
113
113
113
113
Fig. 11


101
107
108
140
107
108
102
108
107
140
107
108
102
101
101
102
(a)
(b)
100
122
100
124
Fig. 12

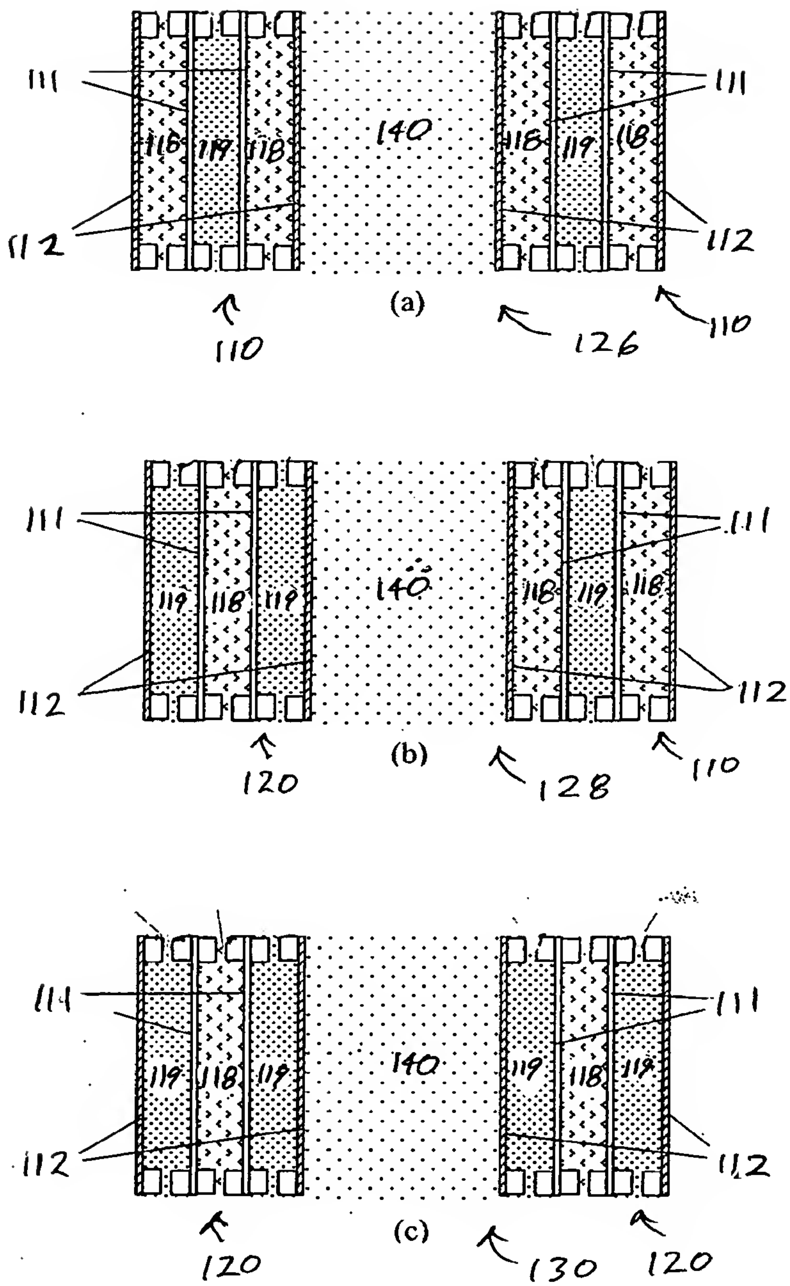


Fig. 13

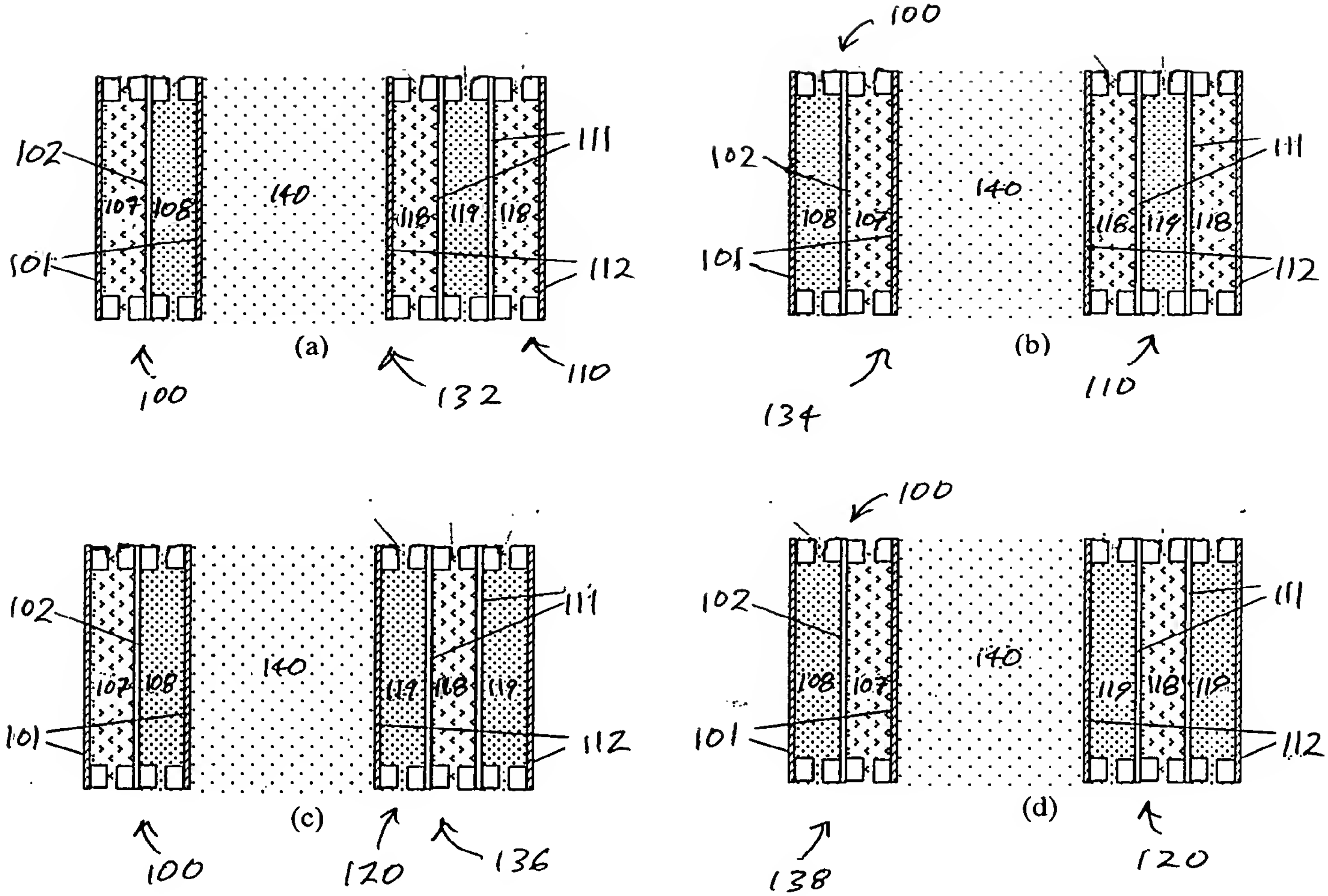

(a)
(b)
(c)
(d)
100
101
102
107
108
110
111
112
118
119
120
132
134
136
138
140

Fig. 14

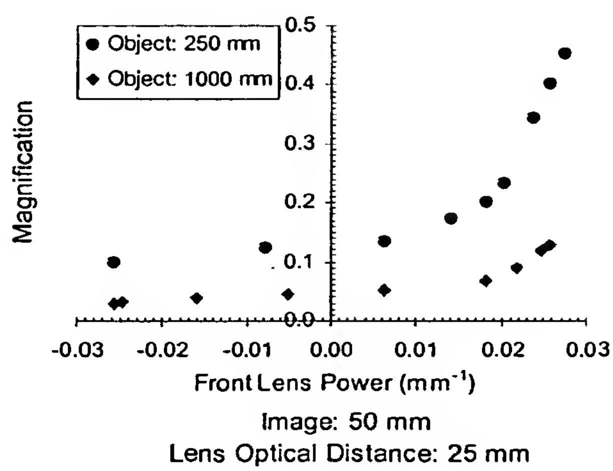

Object: 250 mm
Object: 1000 mm
Magnification
0.0
0.1
0.2
0.3
0.4
0.5
-0.03
-0.02
-0.01
0.00
0.01
0.02
0.03
Front Lens Power (mm^{-1})
Image: 50 mm
Lens Optical Distance: 25 mm

Fig. 15